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AI Applications in Sheet Metal Forming

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AI Applications in Sheet Metal Forming

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Foreword

I am pleased to write a foreword to this book on *AI Applications in Sheet Metal Forming*. Having associated with "Journal of Materials Processing Technology" (previously titled "Journal of Mechanical Working Technology") for around 12 years and being a founder member of the Advances in Materials and Processing Technologies (AMPT) conference series, I have seen many dramatic changes that have occurred in the materials processing domain especially in sheet metal processing. Like many other manufacturing processes, the technology of sheet metal forming has transformed from experience-based craft work to the semi-/fully automated computer-aided processing. Long gone are the days when the process planning and design of tooling for sheet metal work was considered an art rather than science. With the advancement in the domains of computer and artificial intelligence (AI), use of various techniques in sheet metal forming was started in the late 1980s and early 1990s. Nowadays, researchers worldwide are engaged in automation of the tedious and time-consuming tasks of sheet metal forming including product design, process planning and die design by using various AI techniques. However, considerable efforts are still required for actual implementation of this research work in sheet metal industries to convert tedious, time-consuming, and experience-based processing to fully automated processing of sheet metal.

It is with great pleasure therefore to see this new book edited by Shailendra Kumar and Hussein M.A. Hussein focusing on the latest developments in the area of AI applications in sheet metal forming. As the research works of the editors have been presented and published in many AMPT conferences and reputed journals, they are admirably qualified to bring such a book. Authors of chapters of this book are very competent in the domain of material processing. The book is not overly research or academic oriented, but considers the industrial applications of the work. Applications of various AI techniques have been discussed in almost all activities of sheet metal processing including feature extraction, manufacturability assessment, process planning, die design, die modeling, and prediction of die life. Examples of industrial parts have been taken to demonstrate the actual applications of the AI techniques and systems in sheet metal industries. I am sure that this book will be very much useful not only to the researchers and academicians but also a very useful reference for industrial practitioners.

I congratulate the editors on having produced this splendid new book and I convey my best wishes for their success.

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Preface

The innumerable tasks associated with sheet metal forming such as process planning and tool design are complex, time-consuming, tedious, and highly skill intensive. However, there is scarcity of domain experts worldwide to deal with the fast changing demand of high-quality consumer products economically. Moreover, sheet metal industries face challenges of frequent mobility of domain experts without adequate dissemination of knowledge to the new generation of industry professionals. This can be handled effectively by adopting automation in sheet metal industries. Recent advances in the field of Artificial Intelligence (AI) have given rise to the possibility of developing intelligent systems for automation of various activities of sheet metal forming. AI aims at building systems impregnated with some intelligence in their operation or behavior and investigate the way humans perform tasks that require intelligence. Nowadays, number of tools and techniques of AI are widely used in the various sectors of manufacturing.

The primary goal of this book is to incorporate, as much as possible, the state-of-the art development in the applications of AI in the domain of sheet metal forming. The idea to write this book germinated when we had a detailed discussion during AMPT conference held in December 2014 at Dubai.

Our attempts to comprehensively search for availability of book containing research outcomes in the area of sheet metal forming with AI applications prompted us for initiating this task in the absence of any such compiled edition. Since the book was planned to include many topics related to the domain, it would not have been possible for both of us to write all of them on our own. Therefore, it was felt appropriate to approach researchers working in this area to contribute for the different chapters of this book. Professor A.Y.C. Nee, who is one of the pioneers in the domain of material processing, gracefully accepted our invitation to write the introductory chapter for this book.

The book is focused on various applications of different AI tools/techniques in sheet metal forming including feature extraction, manufacturability assessment, process planning, selection of die components, and die modeling. It covers the design of various types of dies including blanking, deep drawing, compound, and bending dies. All chapters of this book present results of dedicated research efforts of authors for years. The book not only highlights the latest research status in the domain but also identifies future scope of work for young graduates. There is no doubt that sheet metal industries will also be benefitted by the research work reported in various chapters of this book.

During the period of preparing manuscript for the book, we have received excellent support from our Ph.D. students and project research fellows especially Mr. Rahul Jagtap, Vikas Sisodia. Ajit Dhanawade, and Ajay Trivedi. We would also like to deeply acknowledge the valuable contributions by authors of various chapters of this book. We would also like to acknowledge the efforts of Ms. Swati Meherishi and her team at Springer for their support in timely publication of this book.

At the end, we would like to dedicate the book to all domain experts and researchers who are directly or indirectly engaged in manufacturing of sheet metal parts.

Surat, India — Shailendra Kumar
Cairo, Egypt — Hussein M.A. Hussein

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Editors and Contributors

About the Editors

Dr. Shailendra Kumar is Associate Professor in Mechanical Engineering Department at S.V. National Institute of Technology, Surat, India. He received his Bachelor's degree in Production Engineering from the Regional Institute of Technology (presently National Institute of Technology), Jamshedpur, India in 1999 and his Ph.D. from the Faculty of Engineering & Technology, Maharshi Dayanand University, Rohtak, India in 2007. His main research interests are in the area of press tool design, AI applications in manufacturing, KBS/expert systems for die design, sheet metal forming, CAPP, CAD/CAM, and non-traditional machining. He is actively involved in many research projects sanctioned by various funding agencies. Four Ph.D. scholars and many M.Tech. students have completed their research work under his supervision. Dr. Kumar has more than 130 research papers in reputed journals and conferences to his credit. He serves as a reviewer for many reputed journals and is a life member of the Indian Society of Mechanical Engineers (ISME), International Association of Engineers (IAENG), and World Academy of Science, Engineering & Technology (WASET), and Senior member of Universal Association of Mechanical and Aeronautical Engineers (UAMAE), IRED, New York, USA.

Dr. Hussein M.A. Hussein is currently serving at the Faculty of Engineering, Mechanical Engineering Department, Helwan University, Cairo, Egypt. He received his Ph.D. in Mechanical (Production) Engineering from Helwan University, Egypt in 2008. He has also served in the tool design department of many companies. His research interests include computer-aided sheet metal die design, AI applications to sheet metal forming, CAD/CAM, AutoCAD application and customization, and CAPP. He has completed many research projects in the area of design and manufacturing sanctioned by various funding agencies. He is a member of the Egyptian Syndicate of Professional Engineers and of the Egyptian Mechanical Engineers Associations.

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An Overview of Applications of Artificial Intelligence (AI) in Sheet Metal Work

A.Y.C. Nee

1 Introduction

Sheet metal working consists of many processes in shaping, cutting, and forming sheet metal parts with various thicknesses. Parts can be as large as automobile bodies to micron-sized components found in medical appliances such as hearing aids. Design of metal stamping dies such as progressive and compound dies is highly complex. Apart from applying scientific principles based on solid mechanics, plasticity and metal forming theories, finite element analysis, etc., a great deal of the current approach is experience-based. Heuristics as well as relying on handbook data and proven tool room practices are most useful to stamping die designers. Knowledge-based techniques, artificial intelligence (AI) tools such as the various evolutionary computation methods have been used to capture the expertise of experienced designers, with various degrees of success. However, most of such approaches are not generic but designed for specific operations as the knowledge base and design rules are quite specific for different operations. From a die designer's viewpoint, knowledge- and rule-based systems are more natural to their practice as he may not be familiar with complex algorithms and AI tools.

Naranje and Kumar (2010) have conducted an extensive review on the application of artificial intelligence applications to metal stamping die design. Kashid and Kumar (2012) also reviewed the use of artificial neural network for sheet metal work. These two articles have covered the recent studies in application of AI tools to sheet metal working comprehensively.

Of the various sheet metal forming and cutting processes such as deep drawing, blanking and forming, fine blanking, press-brake forming, nibbling, etc., the highly productive, although probably the most complex, is the progressive die stamping

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and forming process. Due to the high efficiency and remarkable production rate, progressive sheet metal working has been a norm for mass production of parts used in a myriad of products. Significant consistency in part quality can be maintained within the limits of tool wear.

This introductory chapter focuses mainly on progressive die forming and stamping, highlighting some of the approaches using knowledge bases and artificial intelligence tools.

2 Feature Modeling: Concepts and Techniques

Modeling of sheet metal components usually begins with feature-based methodology. Feature modeling is an approach where high-level modeling entities termed "features" are utilized to associate both geometric and non-geometric information to facilitate design automation. Although feature definition is application-dependent, features can be thought of as building blocks for product definition and geometric reasoning. The characteristics of a feature can be described as (Shah and Mäntylä 1995)

(1) A feature is a physical constituent of a part,
(2) A feature can be mapped to a generic shape,
(3) A feature has engineering significance,
(4) A feature has predictable properties.

A product model can be created solely or jointly using three main classical approaches (Shah and Mäntylä 1995), viz., (1) Interactive feature creation, (2) Automatic feature recognition, (3) Design by features.

The interactive creation method is easy to implement as only the features needed for an application are identified. It may be used to supplement automatic recognition when a reliable algorithm cannot be found, or features cannot be fully formalized. The feature recognition approach is developed for automating the creation of feature models from geometric models. However, exhaustive search of large geometric databases and failure of recognition algorithms are the bottlenecks. One benefit of using the design-by-features approach is that the original design intent can be captured. Another benefit is that it helps to maintain design standardization leading to an improvement in process feasibility and product quality.

Researchers on process planning systems can explore a range of perspectives based on features and other information technology. Planning can be performed at a high level (macro level), where the focus is on an overall selection of production technology, or at the low level (micro level) concentrating on particular processes, operation parameters, sequence, etc. In terms of planning methodology, the plan may be generated by varying existing plans (variant planning), or from scratch based on available generic process knowledge (generative planning). These types of planning activities are not mutually exclusive in design practice.

Feature modeling and reasoning requires the use of object-oriented programming tools. LISP and C++ used to be two of the most popular programming languages for developing feature-based modeling and planning systems (Shah and Mäntylä 1995). Presently, there is a myriad of object-oriented languages such as Python, Objective-C, Smalltalk, Delphi, Java, Swift, C#, Perl, Ruby, PHP, etc.

3 Modeling and Planning for Progressive Cutting Operations

Jagirdar et al. (1995) proposed a feature recognition methodology for extracting shearing features from 2D blank layout. Shearing features are classified into three categories: (1) Inside operations, (2) Boundary operations, and (3) Outside operations. Member operations are further classified into piercing, lancing, shaving, trimming, deburring, blanking, notching, parting, etc. Features are recognized using clear requirement and tolerance for the part. Ismail et al. (1996) developed a progressive die design system for 2D piercing and blanking operations using two approaches to automate the selection of punch shapes and the layout and sequencing of punches. The first approach uses the coding techniques to classify the workpiece geometry. The resulting code is used to select the appropriate punches from a standard library and a sequence of operations is generated. The second approach uses geometric design constraints and is intended for the selection of non-standard punches.

The research work of these two systems has addressed the feature-based modeling and planning of cutting operations in progressive die design well. As bending and forming are 3D, these systems are not able to cover complex operations in progressive forming and cutting. The subsequent section covers the basics of addressing bending and forming operations in progressive die design.

3.1 Bending and Forming Operations in Progressive Die Design

Different from press brake bending operations where a part can be aligned at any preferred orientation to produce a bend feature of a part, in progressive die bending there is only one part orientation for all the stations and bending operations. As a result, more bending types other than a V shape as in press brake bending have to be adopted in a progressive die design. To have better control over the bending process, a designer will need to split a complex or difficult-to-bend structure into a series of intermediate bending states so that the final shape could be achieved with several relatively simple bending operations. Detailed considerations include compensation for spring back, decomposition into partial bending states, and knowledge such as typical bending operations, general bending sequence and other limitations for progressive die bending.

Soft, annealed material with small bending radius may have negligible spring-back, which can be ignored when planning the bending operations. However, spring-back must be compensated at the design stage for bending materials with high spring-back tendency or large radius. Otherwise, it may be very difficult for the toolmakers to address this problem at the production stage, as the required compensation could be too large and exceeds the tooling adjustment limit. Typical spring-back compensation factors and expressions can be found in standard handbooks on metal forming and die design.

To control the bending precision, a bending structure would need to be completed using two or more partial bending operations progressively. This is known as partial bending decomposition, which is needed under the following two circumstances: (1) the bending angle, including compensation for spring-back, is greater than 90° such that it is difficult to be achieved with a single bending operation, and (2) in order to arrange a sub-bend to be performed using a V bend operation, which can provide better control, the "owner" or major bend has to be partially completed in the same operation. There are two optional completing directions which can be applied during planning for the partial bending decomposition, i.e. forward and backward, as shown in Fig. 1.

To produce process plans for a part, a process planning system also requires the knowledge of the processes available as well as their characteristics. Using the lettering representation, L, V, Z, and U are the typical bending types in progressive die bending operations. There are different tooling configurations and precision control associated with each bending type. A complex bending structure can be completed using a series of such bending operations progressively using proven

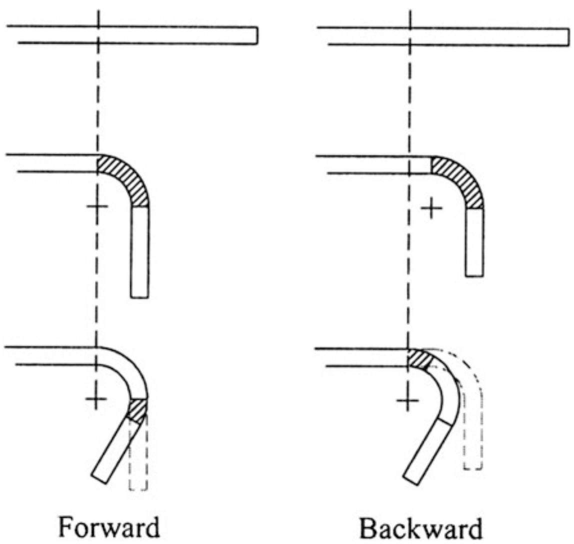


Fig. 1 Partial bending decomposition—forward and backward (Li et al. 2002)

tooling structures. Detailed descriptions of these bending operations are shown in Table 1 (Li et al. 2002). The L bending type is a separate single wall bending while the V and Z bending types refer to the double wall bending of a bend with its zero-degree parallel sub-bend at one station. The difference between the V and Z types is in the configuration of the bending angles of the owner- and sub-bends. The U bending type refers to the concurrent bending of two 180° parallel L, V or Z operations at the same station with approximate symmetric geometry and equal or near-equal bending parameters.

Normally, a progressive die bending operation requires at least a die insert and a punch insert. Either a cam- or rocker-type of the die and punch insert will be required when the absolute bending angle is greater than 90°. A bending type will require a pressure pad to pre-hold the material and lift the part after bending. Ejectors are necessary within the die or punch insert for 90 degree bending.

An L bending can be controlled separately. Using V or Z types can achieve bending up of its sub-wall without the need for pressure pad and a slim punch. V bending is more effective than Z in spring-back control. As U bending is side-force balanced, it is always preferred in process planning.

Many combinations of bending operations can be planned for a part in terms of bending types, sequence, and bending parameters. Determinant conditions such as preferred types of bending operations, limits of bending parameters for each bending type, spring-back control method and direction of bend could be user and case dependent. User preference is based on the design heuristics of the users.

Bending can only be performed after cutting off the outline that is to be bent. Lancing is a special case, in which the cutting and bending are combined into one compound operation using the same punch. However, lancing with a large bending angle or with concatenated bending shapes would normally require one more bending operation following the combined cutting and bending operation.

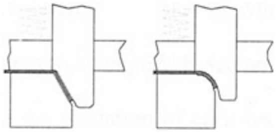
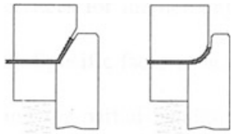
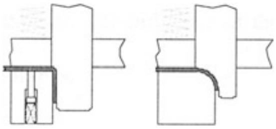
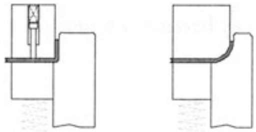
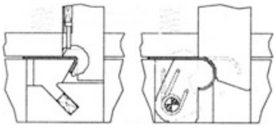
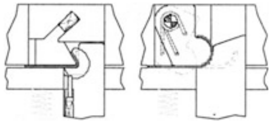
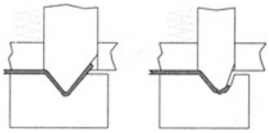
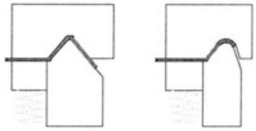
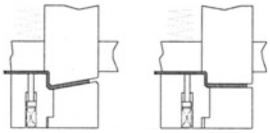
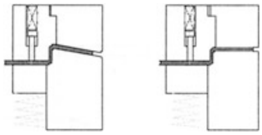
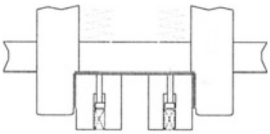
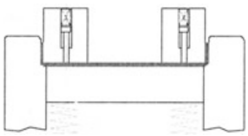
The operations for sub-features such as piercing hole, burring hole, embossing, etc., which may be part of an "owner" bend wall are planned before the owner wall is bent if their relative positions with other bends or sub-features of other bends are not critical. Otherwise, they have to be performed after their owner bend has been completed.

Geometrical and technological information of bending structures and bending operations can be represented by means of bending features which are the building blocks to construct the feature-based planning system. From the geometrical viewpoint, bending can be regarded as the transformation of a flat wall partially or totally into an open cylindrical shell around a bending axis that is parallel to the flat wall.

The offset of the axis to the flat wall is the bending radius and the including angle of the cylindrical surface is the bending angle. Those sub-features located outside the bending zone will only be transformed in position and orientation while those located at or across the bending zone will be transformed in shape as well as by the bending operation.

From a technological viewpoint, there exists a neutral layer of material, which is neither stretched nor compressed during bending. Besides, apparent spring-back

Table 1 Typical bending types in progressive stamping and forming die (Li et al. 2002)

Bending down	Description	Bending up
	Type: “L” Angle: = 90° Tooling Structure: Down: Punch and Die insert Up: punch, pad and stripper insert Springback Control: Over-bending	
	Type: “L” Angle: = 90° Tooling Structure: Down: Punch and Die insert Up: punch, pad and stripper insert Ejector for bend with straight wall Springback Control: Coining	
	Type “L” Angle: > 90° Tooling Structure: Down: Punch and Die insert Up: punch, pad and stripper insert cam or rock insert Springback Control: Over-bending	
	Type: “V” Angle: $\alpha 1 < 90°$, $\alpha 2 < \alpha 1 + 90°$ Tooling Structure: Down: Punch and Die insert Up: punch, pad and stripper insert Springback Ctr: Coining, Over-bending	
	Type: “Z” Angle: $\alpha 1 = 90°$, R2 > Rmin Tooling Structure: Down: Punch and Die insert Up: punch, pad and stripper insert Ejector Springback Ctr: Coining, Over-bending	
	Type: “U” 2 or more concurrent “L”, “V” or “Z” Angle: equal or near equal Direction: same down or up Bending lines: 180° or near 180° Tooling Structure: as “L”, “V” and “Z” Springback Control: as “L”, “V” and “Z”	

may occur due to the large elastic recovery for material with high spring-back tendency. In addition, certain single bending structures may need to be completed progressively by more than one bending operation. Such technological information and requirements also need to be taken into consideration during modeling and planning stages.

3.2 Process Planning of Progressive Dies

Process planning is the most important procedure in progressive die design. The planned strip layout determines the layout angle, material width and pitch, the cutting burr side and forming direction, the number of stations, the operations in each station, and the sequence of operations to produce the specific features of a part. Once the layout is ready, the material utilization can be calculated; the tooling size, tooling cost, the press tonnage and the production rate can be estimated. Such accurate information is helpful for the marketing department to give an early and competitive quotation to the customers. A good strip layout can also be used to guide less experienced designers, since the main issues such as feeding, piloting and parting methods and the precision control schemes have been considered during planning.

Process planning is highly knowledge and experience dependent. A designer has to develop a given part structure into transitional intermediate structures and ensure that these intermediate structures can be achieved with a series of stamping operations based on his expertise and experience. Bending operations in progressive die design have many limitations and constraints (such as feeding requirements, piloting methods and press direction), thus they are more complicated and difficult to design than single-operation die bending and press-brake bending. Knowledge and experience is invaluable especially in predicting and avoiding problems early before the tooling is made. Bends are also among the most common structural features of metal stamping parts used in a variety of consumer electronics, to provide the necessary functions such as stiffening, mounting of other elements, and forming enclosures. In parts made using progressive stamping, among other features such as piercing holes, burring holes, embossments, etc., bends are complex and need to be developed to form flat patterns.

Application of a computer-aided process planning (CAPP) system for progressive die design would be an effective solution to help human planners quickly develop detailed strip layout without the tedious manual calculations and drafting work. Over the last several decades, researchers have been trying to develop different systems at various levels to aid the planning process. However, most of them have achieved limited success, due to: (1) progressive die design is a very complex process, (2) there is a lack of formalized explicit design knowledge, and (3) there is a lack of effective computer-based methods to represent and reuse design knowledge for die design.

Feature descriptions of a part, bend, etc., are convenient input data for the planning system. Based on associated process knowledge, planning rules and user preferences, various planning tasks can be performed. These approaches are known respectively as: knowledge-based, rule-based and heuristics. An early attempt was made by Lee et al. (1993) in designing a knowledge-based process planning system for progressive dies and the approach is able to provide satisfactory solutions to simpler components.

Geometrical and technological information such as reference wall and sub-features, bending line, bending attributes, properties and existing bending operations are essential to process planning and can be retrieved from the bend and part features by their class member functions:

(1) Flat blank of a part feature can be obtained by iterating over outlines of the base wall and all the sub-features. This flat blank can be used to plan the blank layout, the flattened form of the strip layout.
(2) Feature relationships such as owner bend, sub-bend and sibling-bend can be identified by iterating through the base wall and all the sub-features. The bending sequence of a bend in most cases is determined by the relationships between this bend and its owner-bend and sub-features.
(3) Bending line and bending attributes (radius, bending angles) for each bend can be used to examine whether one bend is bending down or up, whether the bend can be completed in one single operation or whether two bends are parallel in opposite direction to each other and hence forming a U bend.
(4) Neutral layer factor controls the geometric mapping of folding, unfolding and partial bending transformation. The estimated spring-back angles would influence the compensation method and the amount of overbending needed.
(5) All the existing bending operations and station numbers for each bend can be inquired thus the completed bending state and the last bending station number can be ascertained before further planning takes place.

3.3 Other Works Using AI Tools for Progressive Die Design and Planning

Artificial intelligence is a loosely used term to refer to a wide variety of computer-based techniques developed to mimic the humans in solving problems. Such techniques include object-oriented, heuristics and rule-based knowledge systems, artificial neural networks, fuzzy logic, genetic algorithms, ant colony optimization, bee colony algorithm, particle swarm optimization, intelligent water drops, etc. Depending on a specific application domain, no one single approach can claim supremacy in solution over other approaches, and as a result, some researchers have used hybrid approaches to complement one another.

A notable research study by Tor et al. (2005) has made a good contribution in using a knowledge-based blackboard framework for stamping process planning. Blackboard architecture, one of the AI techniques, was adopted to develop a blackboard-based system for planning progressive metal stamping dies. As sheet metal stamping die embraces many disciplines including mechanics, material, die, design knowledge, machining, heat treatment, etc., a blackboard approach akin to cooperative decision making is a good application where various knowledge sources can be expressed in different representation schemes including tool room procedures, design rules, etc. An object-oriented system shell CLIPS interfaced with Solid Edge and C++ was used in their system.

More recent studies by Moghaddam et al. (2015), the fuzzy set theory is used to classify and sequence progressive die operations such as blanking, cutting and embossing. The sequencing is planned in two stages. The first stage groups all the operations which can be carried out simultaneously, i.e. in one station, using classification rules. Next, the sequence of the operations is determined using fuzzy rules and sets. Their current system works satisfactorily on several case studies. However, discerning the sequence of pilot holes is noted to be one of the issues yet to be resolved. Other works using the fuzzy set theory to determine bending sequence include Ong et al. (1997) and Kim et al. (2006).

Object-oriented methodology has been a favorite approach adopted by many researchers in the past. An object is simply a distinguishable component of a system which has a set of attributes that defines its characteristics and the associated methods for making the component. Jiang et al. (2006) use an object-oriented approach in designing inserts for progressive metal stamping dies. A flexible and complete insert representation scheme is proposed and the assembly relationships and constraints between the inserts and components are analyzed. In terms of function, inserts can be classified as: punch insert, die insert, stripper bush, clamping insert, etc. Each category has different function. Basing on the different stamping operations, the inserts can be grouped into blanking insert, piercing insert, bending insert, burring insert, embossing insert, etc. The preliminary requirement of insert design is to define the die structure and the operation features, as the insert has a complex assembly relationship with both the die plates and operations. Their work presented a systematic representation scheme of inserts using an object-oriented, feature-based approach. The representation considers the complex interrelations between the components of both vertical and horizontal assemblies, and the design rules and methods for the configuration of insert components such as shoulder, screw, etc.

Knowledge-based systems are widely used in design and manufacturing. There are many researchers who have used this approach in progressive die design. Kumar and Singh developed an intelligent system for automatic modeling of progressive die components using knowledge-based system modules (Kumar and

Singh 2007). Their system allows the users to model the strip-layout based on a number of well accepted rules and heuristics, and then use the generated output data to execute the knowledge-based modules of the die components for automatic modeling of a progressive die. They claimed that their system is a low cost alternative for die designers working in small and medium sized sheet metal industries.

Many decisions made by humans are not reasoned from first principles. Instead, when confronted with a decision making task, the human would first try to relate the problem at hand to the nearest situation he has experienced in the past. He will then try to adopt his past experience to solve the problem at hand. The die designer also commonly uses this case-based approach. When designing a die for the mass production of a component, he will try to recall if he has worked on a similar product previously. If he has, he will retrieve the drawings and use them as a reference for his new design. Computerized die design systems based on the case-based approach could provide benefits as follows:

(1) The design, which is based on an earlier proven working model, will definitely work well
(2) The design will probably be one of the "best" solutions since only good designs will be stored as cases in the design database
(3) There is a better chance that components used in the earlier design may be recycled for use in the new design
(4) The experience of a die designer will not be restricted to those he has worked on in the past. Instead, he will have access to all the good designs developed by the company.

Cheok et al. (1994, 1996) developed a knowledge- and case-based system for designing progressive dies incorporating 3D bending and forming features. Their system is capable of providing semi-automatic solutions for components of moderate complexity.

Skeletons or medial axis have been used to simplify the descriptions of geometrical shapes such that certain geometrical features can be efficiently extracted for image processing or design automation. The concept of using enhanced simplified line (ESL) skeleton for punch shape recognition has been proposed by Cheok et al. (1997). In an interactive design environment, skeletons and their associated properties would need to be generated quickly. The generation of skeletons for a shape with complex geometry and with many holes is computationally intensive as the time to compute the skeleton is proportional to the cube of the total number of edges. A parallel ESL skeleton extracting (PESL) approach is used to address this issue. This approach divides a die plate with holes into a set of sub-polygons, (Fig. 2). The skeletonisation of each of the sub-polygon will consume much reduced computing resources compared to the initial shape. The algorithm for the PESL is designed such that the skeletonisation of the sub-polygons can be carried out in parallel to take advantage of multi-processor workstation to further improve

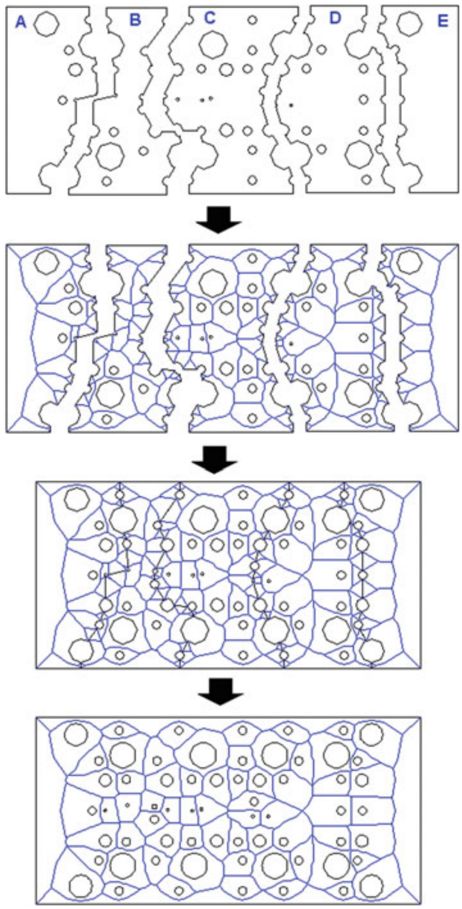


Fig. 2 Extraction and merging of skeletons for a die plate (Cheok et al. 1997)

the response time of the skeletonisation process. This approach has proven to be very efficient when skeletonising complex sheet metal parts and die components to aid decision making in an interactive computer-aided product and tooling design environment.

3.4 Summary

Many computer-aided systems for progressive die design have been attempted by researchers in the last three decades. As computing power increases and more intelligent computational tools are made available, recently developed systems are more powerful and can provide solutions close to, if not better than, those provided by the die designers.

This chapter serves to present a brief overview of some of the works in progressive die design and planning using knowledge-based and AI systems. The subsequent chapters in this book will cover the intelligent tools and techniques in great details in providing solutions to the various sheet metal stamping, forming and cutting processes.

In conclusion, human design knowledge is still central in providing solutions as sheet metal working die design has often been viewed as an art as much as a technology. Many prototype systems developed at the universities have often met with partial degrees of success when applied in the industry, due partly to the following reasons. Firstly, many die designers have acquired their knowledge not from formal tertiary education, but through long periods of apprenticeship. They are more used to interpreting product design and die layout using 2D drawings, traditionally known as blue prints. It is necessary to change their mindset in understanding and interpreting 3D solid models. This concern can be overcome by readdressing the tool and die engineering curriculum in colleges and train the designers to view metal stampings as 3D objects containing functional features. Secondly, experienced die designers have great pride in their work and often view their work as personal and hard-earned intellectual properties. They would resist the idea of having some of their best practices encapsulated in the computer programs for everyone to use. This concern is for real, and is much more difficult to overcome and it would require tactful management persuasion to seek their cooperation.

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Generic Classification and Representation of Shape Features in Sheet-Metal Parts

Ravi Kumar Gupta, Yicha Zhang, Alain Bernard and Balan Gurumoorthy

1 Introduction

Collaboration usually involves actors from different applications. These actors may be software, personnel of different disciplines and skill levels. These actors have to process data from different sources in different formats. Each actor has different need and interpretation of product information, e.g., for manufacturing operation, the information required is how to create the required shape which needs CAD model with shape information, tools, and manufacturing parameters for manufacturing the chosen shape. If the manufacturing operations involved are material removal only then the shape to be manufactured should be interpreted as negative features (classes of shapes representing subtraction of volumes only). For tolerance analysis, the information required is for performing tolerance studies and optimizing tolerance budgets, e.g., different types of dimensions (height, depth, radius, diameter, etc.), numerical tolerances on dimensions, geometrical tolerances with the whole range (form, profile, run-out, orientation, and location), surface finish values and types, multiple attributes to customize dimensions about a part.

Exchange of product data has undergone considerable evolution since the days of annotated engineering drawings (Owen 1997). At that point the focus was to

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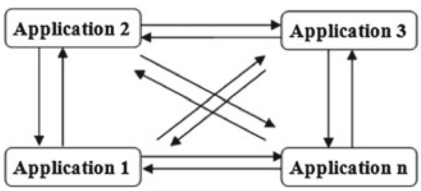
exchange primarily shape/geometric data between design and manufacturing. With the advent of computer-aided design and drafting systems, exchange of shape models between different CAD/CADD applications was required (Gupta and Gurumoorthy 2008a). Different approaches being used to handle the exchange of product model among applications of product development are: (i) a single CAD environment for all tasks, (ii) direct data transformation between different systems which requires '($n * (n - 1)$)' translators for 'n' applications (Fig. 1a) and, (iii) data exchange using neutral file formats (like IGES, STEP or STL) which requires '($2 * n$)' translators for 'n' applications as depicted in Fig. 1b.

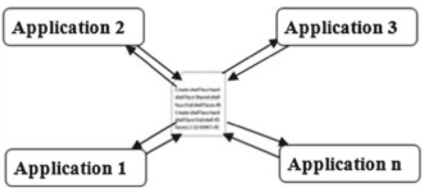
Use of neutral format therefore became the preferred framework to solve the data exchange problem. The Drawing Exchange Format (DXF) is the defacto neutral format used to exchange 2D drawing data across different drawing tools. Then, Initial Graphics Exchange Specification (IGES), another neutral format, was introduced for exchange of geometry information between dissimilar applications. IGES however, is capable of transferring only the geometry of the product; the nonfeature information and design intent are lost. Standard Exchange of Product data model (STEP, formally ISO 10303) evolved to interrelate all geometric and nongeometric data in a useful and meaningful way to represent product content model so that the complete description can be exchanged among CAD systems. STEP data is at present the most comprehensive standard to address the needs for exchange of geometric data.

Exchange of geometric and topological information through STEP, IGES, 3DXML, PLM-XML, and X3D does not have explicit definitions so it cannot be modified. The exchanged information with explicit definitions can be understood by receiving application and can be used and modified as it was developed in the receiving application. Part modeled in application 'A' (Fig. 2a) is exchanged using IGES to application 'B' (Fig. 2b). The exchanged model does not have feature labels and associated meanings. Whereas part model shown in Fig. 2c has feature labels and meanings so it can be modified when required.

Current art in exchange of product data is at the level of exchanging feature models. Feature-based product data exchange is emerging to accommodate design intent for data exchange. Features are capable of carrying constraints, parameters, and application attributes. In the product development cycle, several applications (engineering design, industrial design, manufacturing, supply chain, marketing,

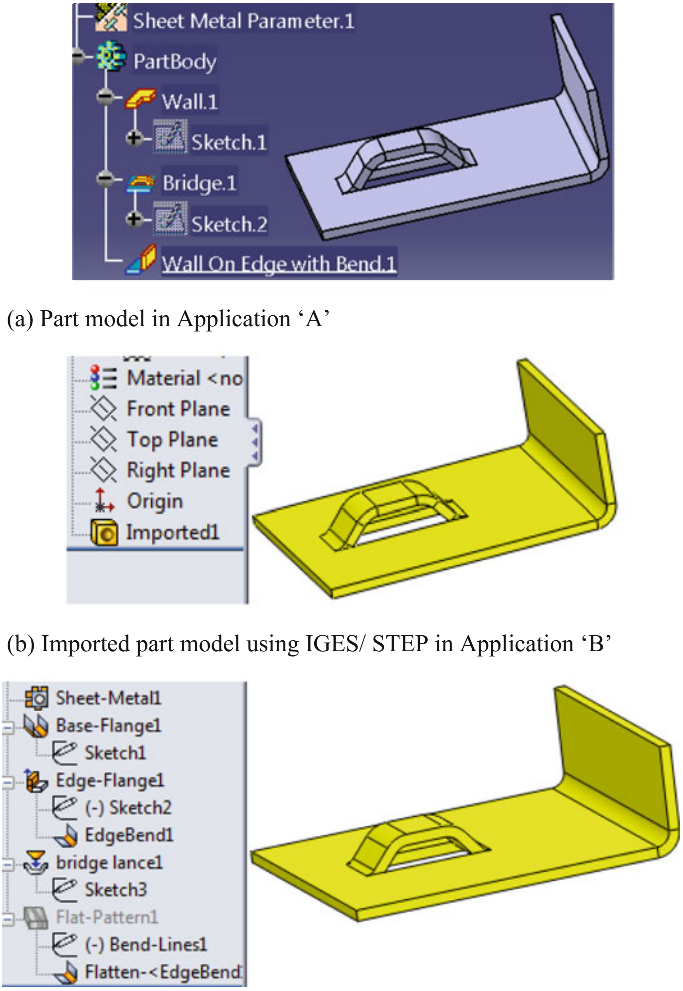


(a) By Direct Translators



(b) By Neutral Format

Fig. 1 Product data exchange



(a) Part model in Application ‘A’

(b) Imported part model using IGES/ STEP in Application ‘B’

(c) Part model in Application ‘B’

Fig. 2 Example of exchange of product information versus feature labels and meanings

maintenance, etc…) and different engineering domains (mechanical, electrical, electronic, etc…) require the ability to exchange product data with feature labels and their meaning. With product development happening in multiple locations with multiple tools/systems, the exchange of product information along with feature labels and their meaning between these tools/systems becomes more important.

Features are described by Shah (1991) as “Features encapsulate the engineering significance of portions of the geometry of a part or assembly, and, as such, are important in product design, product definition, and reasoning, for a variety of applications.” In literature terms ‘shape feature’ (Falcidieno and Giannini 1989;

Sonthi et al. 1997; Brunetti and Grimm 2005) and 'form feature' (Coles et al. 1994; Nalluri 1994; Jha 1998; Subramani 2005) are used for features associated with addition or subtraction of volume to/from a base-solid. These are also defined as machining features (Kailash et al. 2001; Sunil and pande 2009) if features are associated with subtraction of material and can be realized using machining operations.

A feature is defined as the smallest building block that can be modified individually (Kulkarni and Deshpande 2008; Tickoo and Maini 2010). A part in a product is a combination of a number of individual features and each feature is related to other features directly or indirectly. These individual features are capable to carry constraints, parameters, and application attributes important for other applications. Generally, engineers/designers relate information to the features. Information necessary for other application can be attributed to these features and can be used when required. Hence, features are interfaces between shape models and applications (Wong and Leung 1995; Shah and Mäntylä 1995; Brunetti and Grimm 2005; Langerak and Vergeest 2007). The features can also be considered as interfaces for the construction of a shape model, its modification, and application-specific reasoning (Shah 1991).

Formal and unambiguous representations of shape features in a sheet-metal part model are required to exchange feature (feature label and meaning) among applications across product development life cycle. The representation should be unique and application independent so that multiple applications can work together using single representation of a sheet-metal part model. In general, the sheet-metal features in a part model are classified as follows:

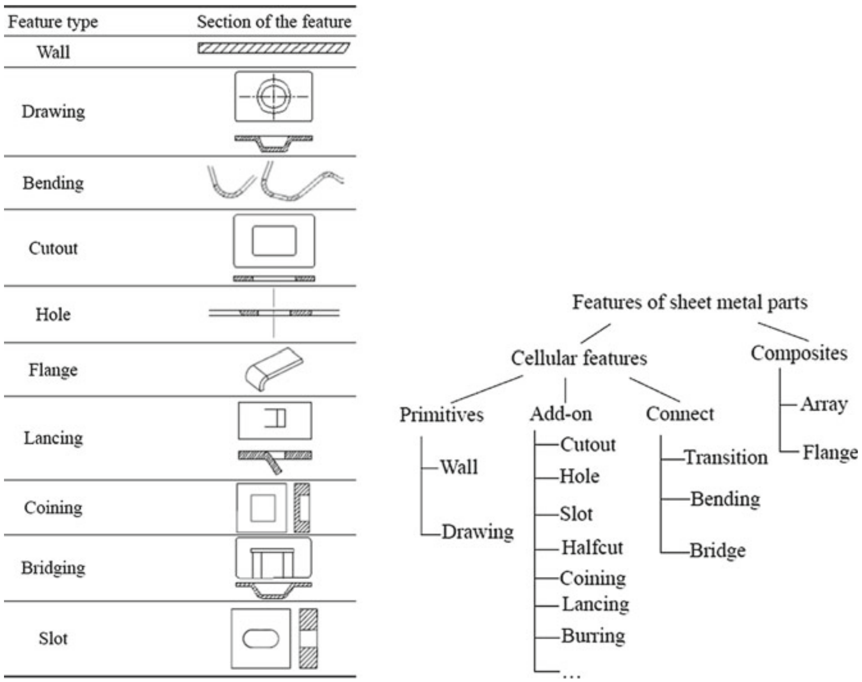
i. Volumetric sheet-metal features as a result of material removal operations on base-sheet (e.g., piercing/blanking operation);
ii. Deformation sheet-metal features as a result of deformation/modification of base-sheet or forming operation on base-sheet.

Researchers worldwide have focused on developing systems for classification and recognition of volumetric features from CAD models using techniques like rule-based (Henderson and Anderson 1984), syntactic pattern recognition (Prabhu and Pande 1999), graph-based (Venkataraman et al. 2001), volume decomposition-based (Woo 2003), hint-based (Vandenbrande and Requicha 1993), artificial neural Networks (ANN) (Shah et al. 2001; Babic et al. 2008; Sunil and pande 2009) and hybrid (Gao and Shah 1998). Comprehensive review of various volumetric feature recognition and classification techniques was reported in the literature (Shah et al. 2001; Babic et al. 2008). The feature classification proposed by Seo et al. (2005) is for feature modeling/construction available in existing commercial CAD systems for volumetric features.

Classification, representation, and extraction of deformation features in constant thickness part model such as sheet-metal have not received much attention in the literature. Many methods have been proposed for the recognition and representation of form features in solid models (Falcidieno and Giannini 1989; Nalluri 1994; Han 2010) but only a few techniques have been reported by researchers to recognize deformation features, based on solid model (Liu et al. 2004; Kannan and Shunmugam 2009) or surface model (Lipson and Shpitalni 1998; Joshi and Dutta 2003). In the stamping industry, the customers and suppliers often use different CAD tools which use different terms with different meanings and formats. The translation of a model results in a loss of the crucial engineering information for the downstream applications.

Liu et al. (2004) have classified features of sheet-metal parts into two categories—cellular features (basic features forming the sheet-metal part) and composites (features integrated as a whole by other kind of cellular features: Array, Flange). Cellular features are further categorized as Primitives (exist in sheet-metal part independently, e.g., Wall, Drawing), Add-ons (added to other features to form sheet-metal part, e.g., Cutout, Hole, Slot, Lancing, etc.), and Connects (acting as a bridge between different types of features, e.g., Bending, Bridge and Transition). This classification of shape features (Liu et al. 2004) along with the sections of these features in sheet-metal part is presented in Fig. 3.

Manufacturing feature classification for sheet-metal features has been presented by Kannan and Shunmugam (2009). The manufacturing features in sheet-metal parts are classified into four major classes: cut, stretched, drawn, and bent as



(a) Typical sheet-metal features (b) Classification scheme of sheet-metal features

Fig. 3 Classification of shape features in sheet-metal parts (Liu et al. 2004)

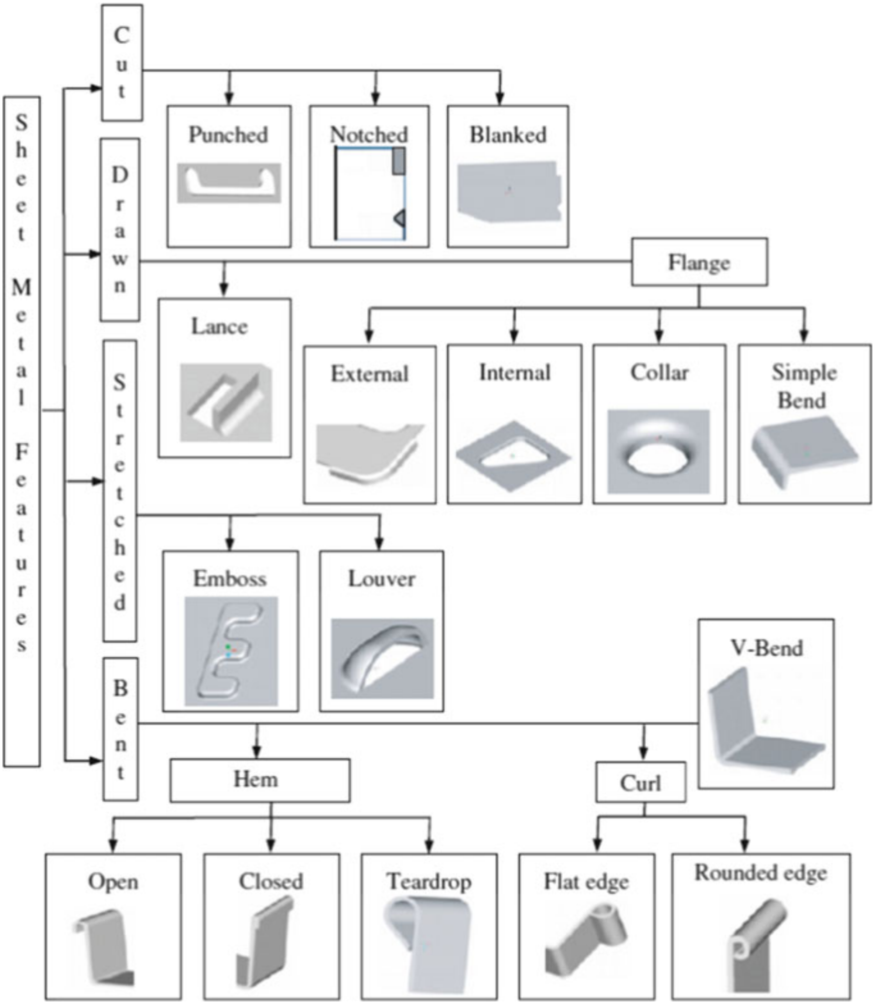


Fig. 4 Classification of manufacturing features in sheet-metal parts (Kannan and Shunmugam 2009)

presented in Fig. 4. The major difference between stretched and drawn features is that a change in sheet thickness occurs in the stretching operation whereas uniform sheet thickness is maintained in the case of a drawing operation. However, for the sake of convenience in modeling, a uniform sheet thickness is used by designers for both features. Bent and cut features involve pure bending and pure shear, respectively. Some features, like internal flanges, require a cut feature before flange is produced.

Sheet-metal feature recognition library (Geometric Limited 2012) operates on boundary representation (B-rep) of solid and surface models and is also available in commercial CAD modeling software. The algorithm in the recognition needs thickness of the sheet-metal part and a reference face to initiate the recognition. Unfolding and folding are used as intermediate step for the recognition of sheet-metal features. The recognized sheet-metal deformation features including Wall, Bend, Flange, and Stamp.

A generic classification scheme based on the classification proposed in literature (Liu et al. 2004; Kannan and Shunmugam 2009; Gupta and Gurumoorthy 2008b, 2013) and application domain (Geometric Limited 2012) is presented in this chapter for the shape features in a sheet-metal part model. DIFF (domain independent form feature) model proposed by earlier researches (Nalluri 1994; Subramani 2005; Gupta 2012) is adopted for representation, classification, and extraction of the sheet-metal features. The representation, classification, and extraction procedures of the sheet-metal features are based on topology and geometry. The definition presented for a feature is unambiguous and application independent and proposed to handle equivalences between feature labels and their representations among applications. The definition proposed for a feature can also be extended to include application-specific information.

2 Sheet-Metal Parts

Sheet-metal parts are created from a large rectangular sheet of constant thickness. The model of a sheet-metal part is first created in a CAD modeling software or on a paper sheet. Once the design is completed then it is sent to pattern-making department where master pattern is generated with different features available in the sheet-metal part and additional features required to achieve the part. After that the master pattern is sent to manufacture the sheet-metal part. Sheet-metal has applications in automobile, aircraft, shipbuilding, HVAC works, medical tables, architecture, farming, reactors, roofs for building, etc. The parts are designed and analyzed according to the application and then manufactured. There are some similarities and dissimilarities in creating sheet-metal parts with solid parts. Similarities, has base-feature, include sketched and placed features, features are created in sequence. Dissimilarities are, a sheet-metal part has a constant thickness, flat patterns created for manufacturing drawings, a feature can be added to a flat pattern that may not appear in the folded state.

3 Sheet-Metal Features

Sheet-metal can be cut and/or bent into a variety of shapes/features. Sheet-metal features are different from volumetric and surface features. These features can be considered as transition between volumetric and surface features. Many researchers consider sheet-metal features as solid models with constant thickness (Lipson and Shpitalni 1998; Liu et al. 2004). Researchers also consider sheet-metal features as surface models (Cavendish 1995; Joshi and Dutta 2003; Nyirenda and Bronsvoort 2008). But some sheet-metal features are created by removal of material, some are created by deforming the sheet-metal, and some are created by cutting partially and then deforming that partially cut portion of the sheet-metal.

Shape features in a sheet-metal part model can be associated with volume subtraction from base-sheet or deformation/modification of base-sheet (or base-surface) or forming of material of base-sheet. The shape features in a sheet-metal part model are classified as (i) Volumetric features, and (ii) Deformation features. These features are also classified as '2-dimensional (2D) features' (volumetric features) and '3-dimensional (3D) features' (deformation features) as a result of modification and forming of base-sheet. Examples of sheet-metal features in a sheet-metal part are presented in Fig. 5. This classification of sheet-metal features is based on volume subtraction and deformation of base-sheet. The volumetric and deformation features are further classified based on topology and geometric information present in the sheet-metal part model (Boundary Representation). Features in the classification are considered as generic features as the classification is independent of application-specific information. Features in sheet-metal parts can also be classified based on context/application information or refined geometric information and considered as nongeneric features. This classification is presented in Fig. 6. The generic classification and representation of volumetric and deformation features is explained in the following sections.

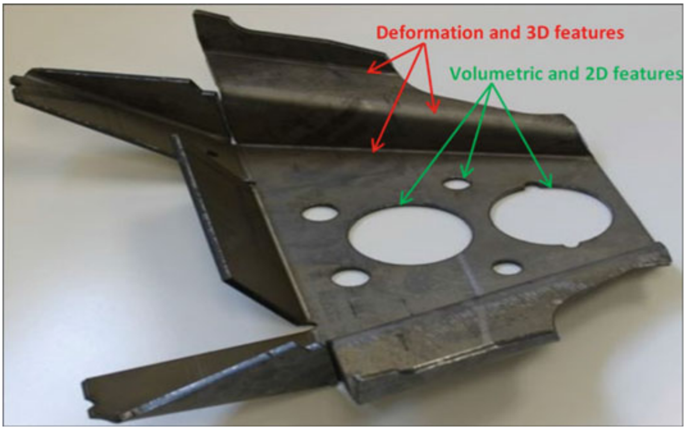


Fig. 5 Example of sheet-metal features in a sheet-metal part (Panghal et al. 2015)

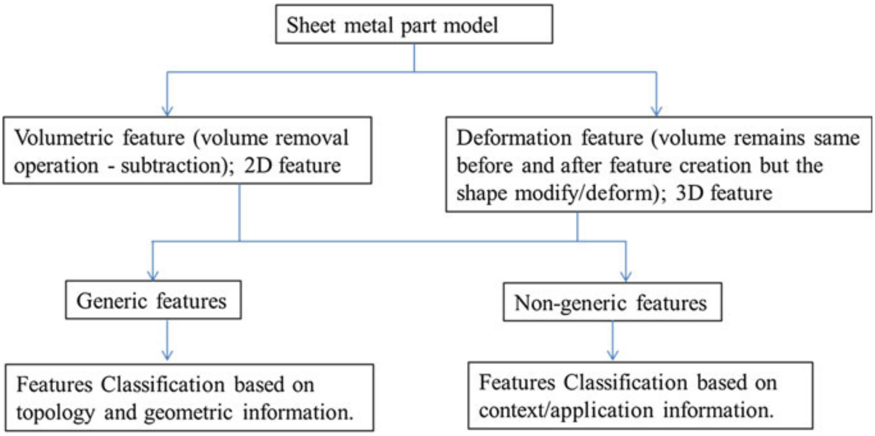


Fig. 6 Sheet-metal features based on volume subtraction and defamation

4 Volumetric Sheet-Metal Features

Sheet-metal piercing/blanking operations involve material removal/cut portion of sheet-metal to get the desired shape. So the result of piercing/blanking operation is negative volumetric feature. As the thickness of sheet-metal part is considered as constant throughout the part model and is also constant for the features so these features are also considered as 2D sheet-metal features. A sheet-metal part is first unfolded (flattened) to find out and mark stamping/blanking profile for the manufacturing. So the cut features has to be defined on the basis of the unfolded part model. If the cut is seen on a bend or bend-flat surfaces then also it will be identified on the unfolded part model.

Volumetric features in sheet-metal part model are results of material removal operations on base-sheet. These types of features are classified based on placement of the features in the part model and type of 2D profiles used in the material removal operations. Volumetric features such as hole, slot, cutout, chamfer, fillet, vent, notch, clip, etc., are created by material removal operations such as cutting, punching, stamping, shearing, nibbling, sniping, notching, clipping, blanking, etc. Examples of volumetric features in sheet-metal parts are depicted in Figs. 7 and 8. The volumetric feature thus created has (i) a 2D profile which is used for shearing operation, (ii) end faces which are shared by faces of the base-sheet and the created feature, these end faces are referred as Shared End Faces (SEFs), and (iii) newly created shell faces in the feature as a result of shearing operation are referred as Created Shell Faces (CSFs). The characteristic arrangements and type of '2D profile', 'SEFs', and 'CSFs' are used to classify generic classification of volumetric features in sheet-metal part model. The type of 2D profile, number, and arrangements of CSFs and SEFs can also be used to define nongeneric information for a volumetric feature.

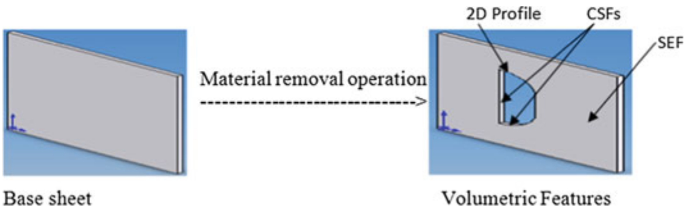
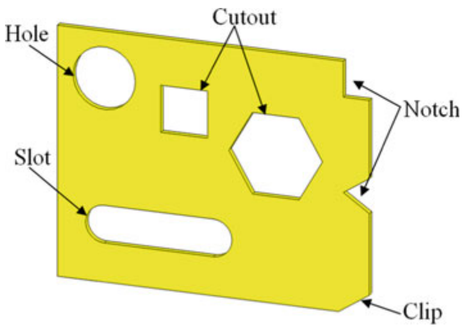


Fig. 7 Volumetric features in sheet-metal part

Fig. 8 Examples of volumetric features in sheet-metal part



4.1 Classification Based on Placement of 2D Profile

The classification based on placement of 2D profile presented in this subsection is considered as generic classification of volumetric features in sheet-metal part models. The placement of 2D profile with respect to the sheet-metal part model is used for classification of volumetric sheet-metal features as **Interior** and **Boundary**. This depends on the placement of feature's profile with reference to the part's outer boundary and can also be identified based on type of 2D profile. If the 2D profile is closed then the feature is Interior else the feature is Boundary.

Interior volumetric feature lies inside the part model. The feature profile is closed and completely inside the part's outer boundary. Example of the interior feature is presented in Fig. 9.

Boundary volumetric feature lies on the part's outer boundary. The feature profile is opened. The feature profile and part's outer boundary are interesting or some portion is common to the both. Example of the boundary feature is presented in Fig. 9.

4.2 Classification Based on Shape of the 2D Profile

The classifications based on shape of 2D profile presented in this subsection are considered as nongeneric classification of volumetric features in sheet-metal part

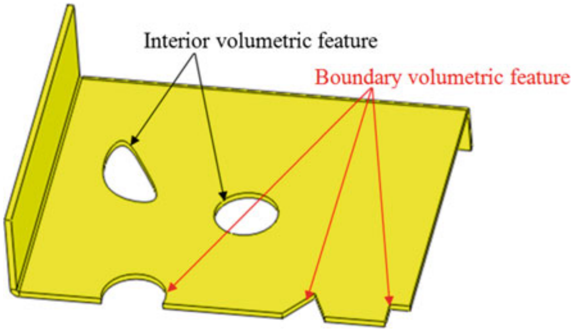
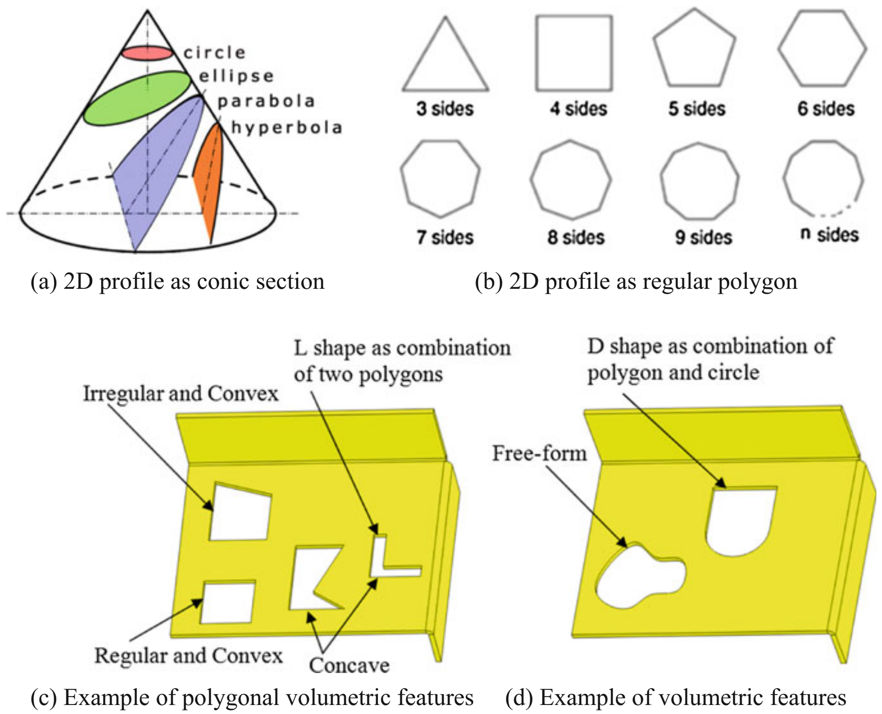


Fig. 9 Example of interior and boundary volumetric sheet-metal features

models. This is considered as nongeneric information as it is too specific to geometric information and can be required for specific application as opposed to the generic classification where the classified information is required for most of the applications considered. The classifications based on shape of 2D profile of a volumetric feature is considered as the classification based on 'number of edges', 'type of edges', and 'angle between two adjacent edges' in the 2D profile.

If shape of the 2D profile in a volumetric sheet-metal is a conic section (e.g., circle, ellipse, parabola or hyperbola as shown in Fig. 10a) then the volumetric feature is classified as circular, elliptical, parabolic, or hyperbolic volumetric feature, respectively. If shape of the 2D profile is a polygon (e.g., 3-sides, 4-sides, … n sides as shown in Fig. 10b) then the volumetric feature is classified as 3 sides, 4 sides, … n sides polygonal volumetric feature, respectively. The number of planar CSFs in the feature defines the type of polygonal volumetric feature in a sheet-metal part model. A polygonal volumetric feature is a regular polygonal volumetric feature if length of all edges in 2D profile is same and angle between adjacent edges is same else it is irregular polygonal volumetric feature. Examples of regular and irregular volumetric features are presented in Fig. 10c. 2D profile in a volumetric feature can be a combination of conic section(s) and/or polygon (s). For example, "L shape volumetric feature" as a combination of two rectangular polygons is shown in Fig. 10c and "D shape volumetric feature" as a combination of polygon and circle is shown in Fig. 10d. If angle between any two adjacent edges in a 2D profile of a volumetric feature is more than 180° then the volumetric feature is classified as concave else it is convex. Example of concave volumetric features and convex volumetric features are presented in Fig. 10c. If the 2D profile of a volumetric feature is not classified as conic section and/or polygonal, then the feature is a free-form volumetric feature (see Fig. 10d). Further classification based on nongeneric information, such as material information, actual dimensions, and application specific information, is not covered in this chapter. This nongeneric classification and information can be built as per the requirements.

The classification of volumetric features in sheet-metal parts is presented in Fig. 11. Each volumetric feature is classified uniquely based on the combination of four groups of factors presented in Fig. 11. This classification captures the geometric and topological variations in volumetric features.

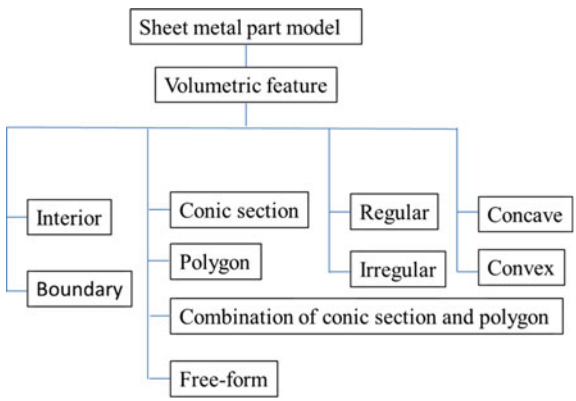


(a) 2D profile as conic section (b) 2D profile as regular polygon

(c) Example of polygonal volumetric features (d) Example of volumetric features

Fig. 10 Type of volumetric sheet-metal features based on shape of the 2D profile

Fig. 11 Classification of volumetric features in sheet-metal parts



5 Deformation Sheet-Metal Features

Deformation features in sheet-metal parts such as bend, flange, jog, hem, dimple, bead, crimp, ribs, embosses, louvers, lances, etc., are created by beading, bending, crimping, forming, folding, turning, joggling, embossing, lancing, louver operation, etc. Examples of deformation sheet-metal features are presented in Figs. 12 and 13.

Deformation features are created in constant thickness part models, for example, deformation of material (as in sheet-metal parts) or forming of material (as in injection molded parts of constant thickness) also referred as constant thickness features (Lipson and Shpitalni 1998; Liu et al. 2004; Gupta and Gurumoorthy 2008b; Geometric Limited 2012). The literature review for classification and extraction of deformation features in sheet-metal parts is presented in paper (Gupta and Gurumoorthy 2013). A classification scheme based on the classification proposed in literature (Liu et al. 2004; Kannan and Shunmugam 2009; Gupta and Gurumoorthy 2008b, 2013) has been presented for deformation features to realize their representation and extraction.

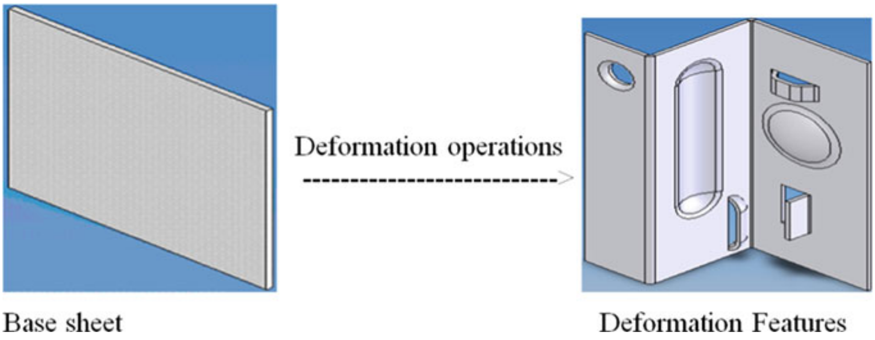


Fig. 12 Deformation features in sheet-metal part

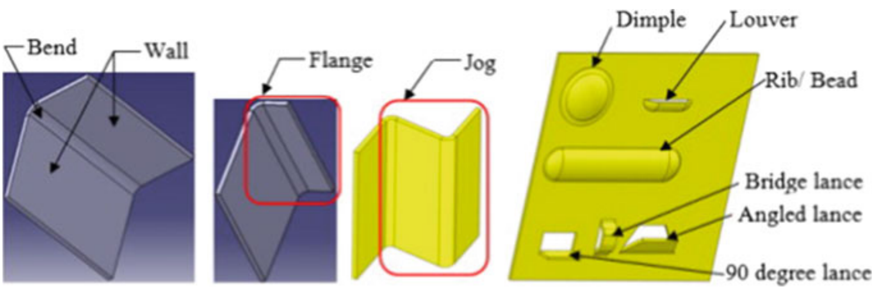


Fig. 13 Examples of deformation features in sheet-metal parts (Gupta and Gurumoorthy 2013)

The deformation features in sheet-metal part model are identified and represented in terms of faces and adjacency relationships between faces. Deformation of a base-sheet creates Bends and Walls with respect to the base-sheet which are referred as basic deformation features. Deformation features in sheet-metal part model are defined uniquely in terms of Basic Deformation Features Graph (BDFG) with characteristics of shell faces and bends. A deformation feature has certain number of Walls and Bends in particular sequence which is captured in BDFG (Gupta and Gurumoorthy 2013). The arrangement of Walls and Bends in the graph has information related to the classification of deformation features. Definition of Basic Deformation Features Graph (BDFG) and representation of deformation feature using BDFG can be referred in the work of Gupta and Gurumoorthy (2013). The classification of faces and features in sheet-metal parts related to deformation of base-sheet are described in the following sub sections. Some of the commonly used terms in the classification and representation are defined below:

Thickness It is constant for a sheet-metal part. It is the minimum of the shortest distances between pairs of two parallel faces of similar surface type (planar/cylindrical/conical/spherical/toroidal) which have normals in opposite directions as shown in Fig. 14 (Gupta and Gurumoorthy 2013).

It is found that a deformation sheet-metal feature has at least one pair of two concentric faces of similar surface type (as cylindrical/conical/spherical/toroidal) which have normals in opposite directions. The number of faces with surface type as cylindrical, conical, spherical, and toroidal is smaller than that of faces with surface type as planar. So, the thickness is identified as the minimum of the shortest distances between pairs of two concentric faces of similar surface type (cylindrical/conical/spherical/toroidal) which have normals in opposite directions as in Fig. 14b so that less number of surfaces are processed to find the thickness.

End face versus **Shell face** Faces along the thickness are classified as shell faces as shown in Fig. 14. Faces across the thickness are classified as end faces as shown in Fig. 14.

Wall versus **Bend** Two parallel end faces of similar type (Planar, cylindrical, conical, spherical, or toroidal) with normals in opposite directions and are at an equal distance to thickness are referred as end faces of a BDF (Wall/Bend). Shell faces joining these two end faces of the BDF are referred as shell faces of the BDF

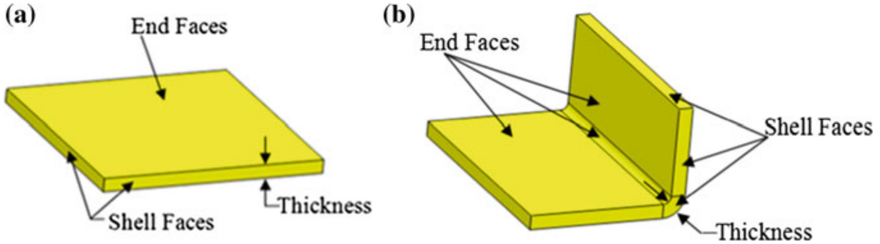


Fig. 14 Thickness, End faces, and Shell faces in sheet-metal part (Gupta and Gurumoorthy 2013)

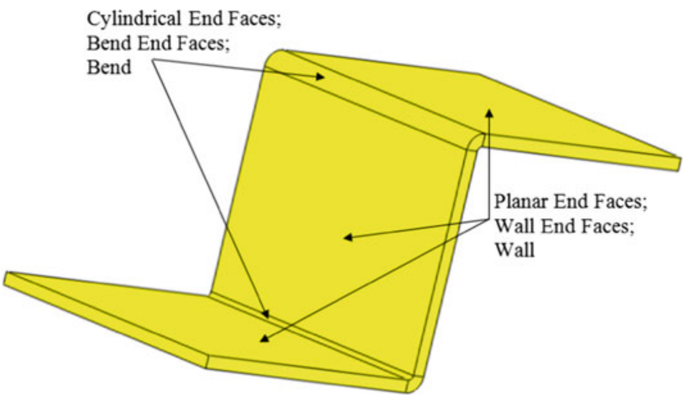


Fig. 15 End faces, wall and bend in sheet-metal part

(wall/Bend). If surface type of end faces of the BDF is cylindrical, conical, spherical, or toroidal then it is Bend, otherwise it is Wall as shown in Fig. 15.

Created Wall End Faces (CWEFs) versus **Created Bend End Faces (CBEFs)** End face is classified as Wall end face or Bend end face depending on the surface types. All end faces in a sheet-metal part are referred as created end faces and are classified as CWEFs or CBEFs depending on the surface type of the face. If the surface type of an end face is cylindrical, conical, spherical, or toroidal, then it is CBEF else it is CWEF (see Fig. 16).

Created Shell Faces versus **Shared Shell Faces** The adjacent faces of two or more contiguous basic deformation features in the deformed sheet which are in the same plane with their normals in the same direction are classified as shared face as shown in Fig. 16a. A face, shared by two or more contiguous basic deformation features in the deformed sheet, is also referred as shared face (Fig. 16b). A shell face of such type is classified as Shared shell face.

A face which is shared by only one basic deformation feature, and there is no adjacent faces which are in the same plane then the face is classified as created face

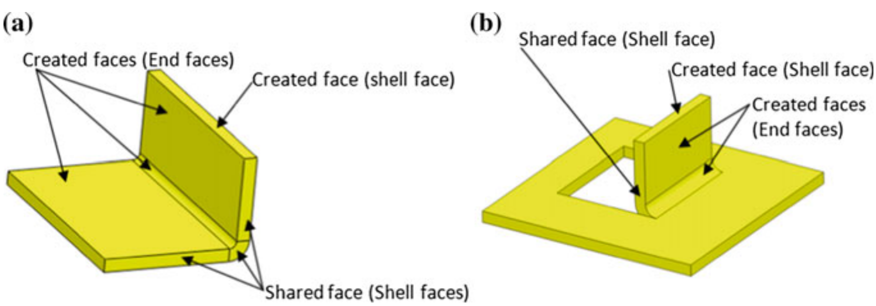


Fig. 16 Shared and created faces in sheet-metal part (Gupta and Gurumoorthy 2013)

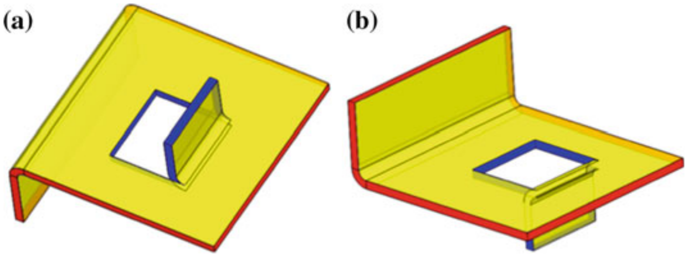


Fig. 17 Sheet-metal part's outer boundary shell faces and interior boundary shell faces

as shown in Fig. 16. A shell face of such type is classified as Created shell face (see Fig. 16b).

Part's outer boundary shell faces versus **Part's interior boundary shell faces** Shell face which has common edge with inner bound edge(s) of an end face is referred as part's interior boundary shell face. Shell face which is contiguous to part's interior boundary shell face is also referred as part's interior boundary shell face. Shell face which is not at inner bound edge(s) of an end face and also not contiguous to part's interior boundary shell face then the shell face is referred as part's outer boundary shell face. Blue color faces are part's interior boundary shell faces whereas red color faces are part's outer boundary shell face as shown in Fig. 17.

Feature's Boundary Shell Faces versus **Feature's Interior Shell Faces** Feature's shell face which is common to part's outer boundary shell face is referred as boundary shell face (Fig. 18a) else the feature's shell face is interior shell face as shown in Fig. 18b.

Base-feature BDF with maximum surface area of an end face is selected as base-feature.

Bend as SimpleBend and SBend in BDFG A bend is a SimpleBend when direction of this bend and previous bend in the graph is same or it is first bend in the graph. A bend is a SBend when direction of this bend and previous bend in the graph are opposite.

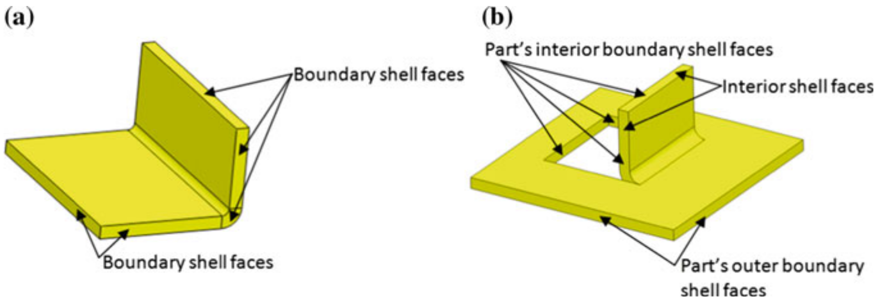


Fig. 18 Sheet-metal feature's boundary shell faces and interior shell faces

5.1 *Classification of Feature Faces for Deformation Sheet-Metal Features*

The faces in a sheet-metal part model associated with an individual "deformation feature" are classified as follows:

Created End Faces (CEFs)—Newly created faces in the base-sheet corresponding to the end faces of the created deformation feature in the deformed sheet. The CEFs are further classified as **Created Wall End Faces (CWEFs)** and **Created Bend End Faces (CBEFs)** depending on the basic deformation feature type as shown in Fig. 19a. Surface types of bend end faces are cylindrical, conical, spherical, or toroidal and are referred as CBEFs. Surface types of wall end faces are planar and are referred as CWEFs. Examples of CWEFs are 11, 14 (Fig. 20a) and 14, 16 (Fig. 20b), CBEFs are 10, 13 (Fig. 20a) and 13, 15(Fig. 20b).

Shared Shell Faces (SSFs)—If two or more adjacent shell faces in a deformation feature are lying in one plane and their normals are in same direction then these faces are classified as shared shell faces (SSFs) as shown in Fig. 19a. One shell face in a deformation feature which is shared by two or more contiguous basic deformation features then also the face is classified as shared shell face as shown in

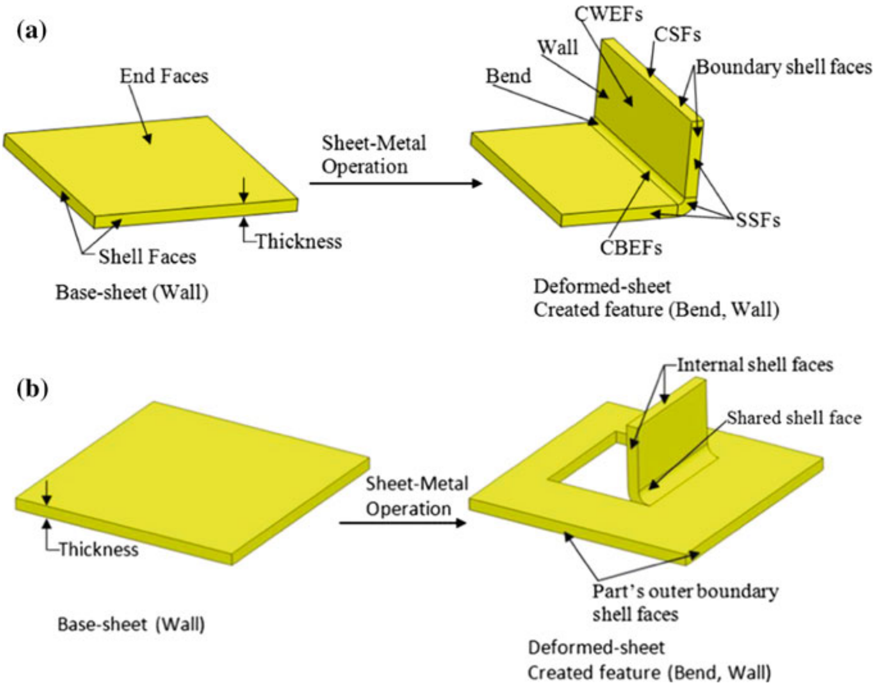
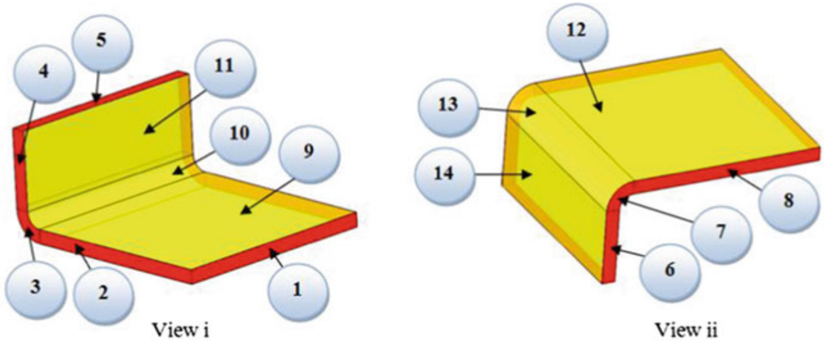
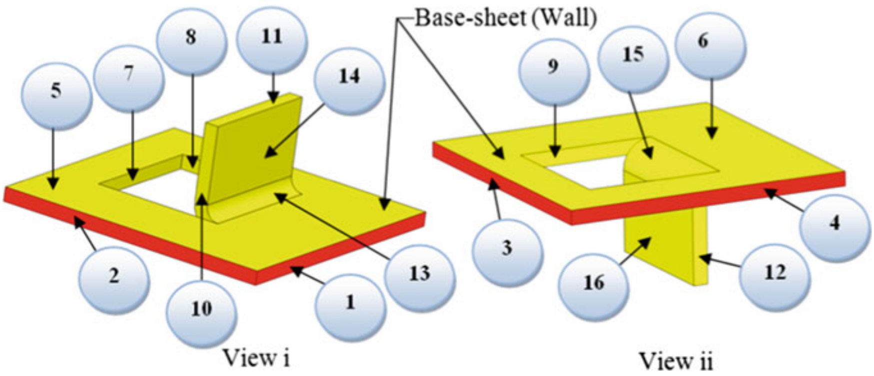


Fig. 19 Classification of feature faces for deformation features in sheet-metal parts (Gupta and Gurumoorthy 2013)



(a) Edge flange



(b) 90 degree lance

Fig. 20 Examples of faces in deformation sheet-metal features (Gupta and Gurumoorthy 2013)

Fig. 19b. The SSFs are further classified as **BSSFs** (Boundary SSFs) or **ISSFs** (Interior SSFs) based on whether the SSF of a deformation feature in sheet-metal part is coinciding with the outer boundary shell face of the part or not. Part's outer boundary shell faces are shown in red color in examples presented in Fig. 20. Examples of BSSFs are {3, 4}, {6, 7} in Fig. 20a, ISSFs are 10, 12 in Fig. 20b.

Created Shell Faces (CSFs)—A shell face in a deformation feature which is shared by only one basic deformation feature, and there is no adjacent shell faces which are in the same plane then the shell face is classified as created shell face (CSFs) as shown in Fig. 19a. The CSFs are further classified as **BCSFs** (Boundary CSFs) or **ICSFs** (Interior CSFs) based on whether the CSF of a deformation feature in sheet-metal part is coinciding with the outer boundary shell face of the part or not. Examples of BCSFs are 5 in Fig. 20a, ICSFs are 11 in Fig. 20b.

Since the deformation sheet-metal features are defined in terms of six types of faces (CBEFs, CWEFs, BSSFs, ISSFs, BCSFs, ICSFs), the feature definitions are consistent and amenable to automated reasoning. Hierarchical structure of classification of these faces in a deformation sheet-metal feature is shown in Fig. 21.

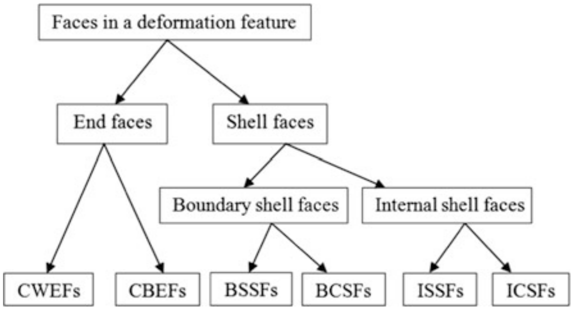


Fig. 21 Hierarchy of classification criteria in feature definition of deformation features (Gupta and Gurumoorthy 2013)

These six types of faces of each deformation feature along with face adjacency relationships are stored in the DIFF model (Gupta 2012).

5.2 Classification of Deformation Sheet-Metal Features

The definition of deformation sheet-metal feature separates the generic content from the nongeneric content. This is similar to the definitions proposed for volumetric sheet-metal features. The overall form and shape of a feature are separated into type and shape. The type of the feature is specified by the generic type and nature whereas the shape of the feature is specified by the actual values of the geometric entities such as angle of bend, length/height of flange, etc. The generic content of the deformation feature is defined in terms of basic deformation features (Wall and Bend) and their characteristics. The number and type of shell faces determines whether the identified feature is generated by partially cutting and subsequent deformation or generated by only deformation of the sheet. Deformation sheet-metal features are classified and represented based on the characteristics of the shell faces and bends. The six types of faces (CBEFs, CWEFs, ISSFs, BSSFs, ICSFs, BCSFs) and type of bends capture the feature form and the feature creation process.

The characteristics of the feature's shell faces and bends are used to classify the deformation sheet-metal features into classes based on three factors described in the following sub sections.

5.2.1 Number and Arrangement of Boundary Shell Faces

Feature's shell faces coincide with the sheet-metal part's outer boundary shell faces are referred as boundary shell faces. Based on this factor, deformation features are classified into four classes as defined below:

Interior These are the deformation features which do not coincide with the outer boundary shell faces of the part. This class of features does not have shell faces

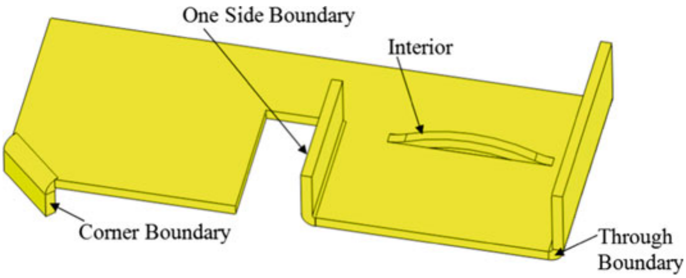


Fig. 22 Examples of type of defamation features based on 'number and arrangement of boundary shell faces'

which are common to the outer boundary shell faces of the part (means BSSFs = 0 and BCSFs = 0). This class of features is referred as *Interior* in the proposed classification. An example of this type of feature in a sheet-metal part is presented in Fig. 22.

One Side Boundary These features are at the outer boundary shell faces of a sheet-metal part. This class of deformation feature either has a coincidence of a single shared shell face of the deformation feature with the outer boundary shell face of the part which means BSSFs = 1 or has BCSFs without BSSFs (means BSSFs = 0 and BCSFs > 0). This class corresponds to a deformation feature referred to as *Boundary* in the classification. An example of the deformation feature, 'One Side Boundary', is presented in Fig. 22.

Corner Boundary This class of deformation feature is identified when any two adjacent shared shell faces of the deformation feature coincide with two adjacent outer boundary shell faces of the part which means this type of deformation feature has two adjacent BSSFs. Since two adjacent faces meet at a corner this class of deformation features is referred to as *CornerBoundary* in the proposed classification. Example of CornerBoundary feature is shown in Fig. 22.

Through Boundary This class of deformation features arises when two non-adjacent shared shell faces of the feature coincide with the outer boundary shell faces of the part and hence, there are two nonadjacent BSSFs. This class of deformation features is referred as *ThroughBoundary* in the classification. An example of this type of deformation feature in a sheet-metal part is presented in Fig. 22.

5.2.2 Number of Interior Shell Faces in a Deformation Feature

Each class based on the characteristics of boundary shell faces is further classified into two subclasses which captures the feature creation process. The classification is based on the number of ICSFs and ISSFs in the deformation feature. These two subclasses are described below.

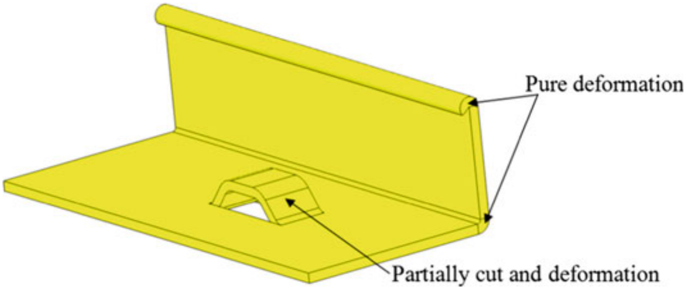


Fig. 23 Examples of type of defamation features based on 'number of interior shell faces in a feature'

Pure deformation This class of deformation features is generated by various stamping/forming processes. Features created by beading, bending, crimping, forming, folding, turning, joggling, embossing operations belong to this category, such as Dimple, Bead, emboss, Surface stamp, Curved stamp, Circular stamp, Stiffening rib(Dart), etc. Deformation features in this class have ISSFs = 0 and ICSFs = 0. This class of features is referred as *PureDeformation* in the classification. A PureDeformation feature can be either interior or boundary (one side, corner, through) based on the interactions of the deformation feature with the outer boundary shell faces of the part. Examples of PureDeformation features (Simple bend (Kannan and Shunmugam 2009), type of hem (Kannan and Shunmugam 2009) in a sheet-metal part are presented in Fig. 23.

Partially cut and deformation Features created by lancing and louver operations belong to this category. This class of deformation features are cut partially and then deformed the cut portion to get the desired shape. Deformation features in this class have one or more interior shell faces (means ISSFs > 0 and/or ICSFs > 0) which corresponds to the partially cutting and deformation of the cut portion to create a deformation feature in sheet-metal part so a deformation feature with ISSFs > 0 and/or ICSFs > 0 belongs to this class. This class of deformation features is referred as *PartiallyCutDeformation* feature in the proposed classification. If the identified feature has shell faces that coincide to the outer boundary shell faces of the sheet-metal part then the deformation feature is on the boundary else it is interior. An example of this type of feature (Bridging (Liu et al. 2004) or Bridge lance (Gupta 2012)) is shown in Fig. 23.

5.2.3 Type of Bends in a Deformation Feature

Each class of deformation sheet-metal features presented in Sects. 5.2.1 and 5.2.2 is further classified into subclasses based on the variations in curvature in the deformation feature. This factor captures the nature of the deformation features. The direction of curvature in a bend or a wall is same. It is different only when a

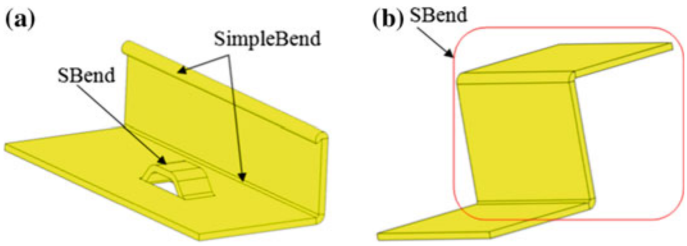


Fig. 24 Examples of type of defamation features based on 'type of bends in a feature'

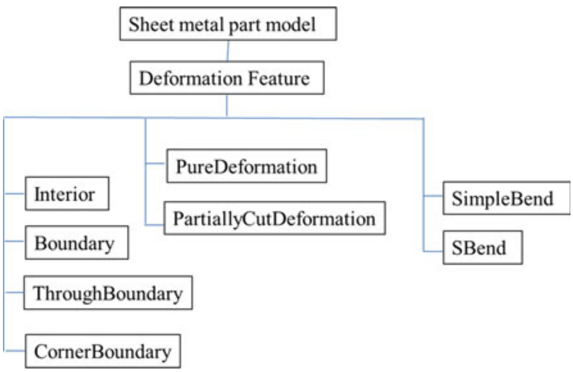
deformation feature has two or more bends and two bends are of opposite directions. These variations in curvature are captured by types of bends in a deformation feature.

Directions of curvature across the deformation feature are used to define feature nature. If the directions are same throughout the deformation feature then all bends in the feature have same type of curvatures (concave or convex) else different types of curvatures means some bends are concave and some bends are convex in nature.

These variations of curvatures in a deformation feature are captured as SimpleBend and SBend to define same type of curvatures and different type of curvatures, respectively, in the proposed classification. A deformation feature with SimpleBend means all bends in the feature have same type of curvature. A deformation feature with SBend means the deformation feature has at least one pair of bends with different type of curvature. These two types of bends create two subclasses as "**SimpleBend**" and "**SBend**" under each class of deformation features based on previous factors. Examples of features with SimpleBend are edge flange (Fig. 24a), hem flange (Fig. 24a), counter sink emboss, 90° lance and angled lance. Examples of features with SBend are jog (Fig. 24b), bead, dimple, louver, arc lance, bridge lance (Fig. 24a), etc.

The classification of deformation features in sheet-metal parts is presented in Fig. 25. Each deformation feature is classified uniquely based on the combination

Fig. 25 Classification of deformation features in sheet-metal parts



of above three factors. This classification captures the geometric and topological variations in deformation features in sheet-metal parts. Definition of Basic Deformation Features Graph (BDFG) and representation of deformation feature using BDFG can be referred in the work of Gupta and Gurumoorthy (2008b, 2013) and Gupta (2012). Complex deformation features (like jog, dimple, bead, rib, lance, and louver) can easily be expressed using BDFG.

6 Conclusion

Sheet-metal can be cut and/or bent into a variety of shapes/features. A sheet-metal part is a combination of a number of individual features and each feature is related to other directly or indirectly. Sheet-metal features are created by removing of material, deforming the sheet-metal, and cutting partially and then deforming that partially cut portion of the sheet-metal. The sheet-metal features are classified into two categories as volumetric and deformation. The generic classification of these features has been presented. The volumetric features in sheet-metal parts are classified based on placement of the feature in the part model and type of 2D profile present in volumetric feature and also used for the material removal operations. Deformation features are classified into type (placement of the feature in the part model and type of feature as pure deformation or deformation followed by partial shearing) and nature (type of bends) based on number, type, and arrangements of faces for a feature in a part model.

The features in sheet-metal parts are classified as generic features based on topology and shape information. These features are also classified based on geometric information and information specific to particular context as nongeneric. The generic information can be considered as common to all the applications involved and can also be used for development of common/shared understanding in the product design and development. The nongeneric information is application-/domain-specific so once a generic feature is identified then the nongeneric information can be built around the generic information for a particular application/domain.

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Feature Extraction and Manufacturability Assessment of Sheet Metal Parts

Shailendra Kumar, Rajender Singh, Deepak Panghal, Sachin Salunkhe and Hussein M.A. Hussein

1 Introduction

Feature recognition or feature extraction of sheet metal parts is a necessary and important activity to support the design and manufacturing automation. The term feature recognition refers to techniques that are able to automatically identify design features of part from its drawing file. Figure 1 depicts some features of a typical sheet metal part. Various features of sheet metal parts mainly categorized into three groups, i.e., shearing features, bending features, and deep drawing features as shown in Fig. 2. There are two methods for feature extraction (i) Constructive solid geometry (CSG), and (ii) Boundary representation (B-rep) (Srinivasakumar et al. 1992). The CSG of the solid model is specified with a set of Boolean operations and a set of 3-D solid primitives. On the other hand, the B-rep of a solid model contains information about faces, edges, and vertices of a surface model and at the same time

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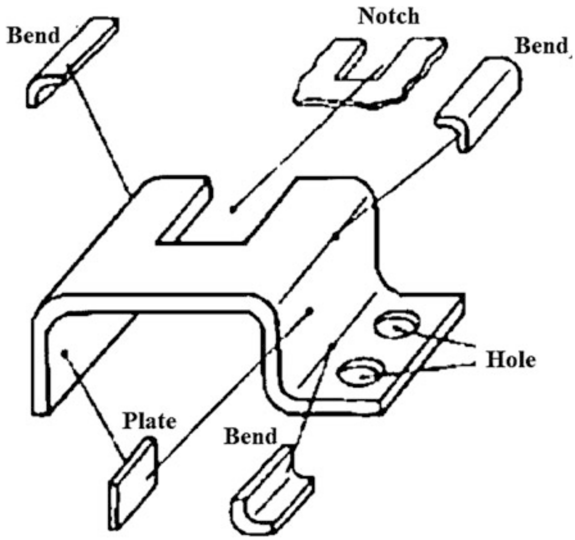


Fig. 1 Design features of a typical sheet metal part (Wierda 1991)

includes topological information that defines the relationship between the faces, edges, and vertices. There are three types of model geometry representations used in CAD software (Subrahmanyam and Wozny 1995)—wireframe model, surface model, and solid model. Wireframe models are composed of points and curves that represent the edge boundaries of product geometry. Complex part geometry is seldom created in wireframe model. However, it is easily and automatically generated by neutral file transfer protocols like IGES and STEP. It is computationally easy to handle when compared to equivalently complex solid models. However, this can be quite ambiguous in regard to what is 'solid' and what is not, requiring human intervention for interpretation of geometry. This ambiguity has traditionally been too complex to handle with automated feature recognition systems. Feature recognition using wireframe models has been explored in the past; however contemporary work has shifted to surface and solid models for reasons of model ambiguity (Shah and Mantyla 1995). Solid models are of two types, the constructive solid geometry (CSG) and boundary representation (B-Rep). CSG models are stored in unevaluated or implicit form, and the final part must be calculated from set theory carried out on solid primitives. B-Rep is an explicit representation of the solid boundary including all vertices, faces and edges. One major advantage of CSG feature trees is that the features may be easily arranged by order of construction or destruction; however, CSG is no longer widely used. To automate the die design process, a computer-aided system is required for automatic extraction of design features of sheet metal parts.

Manufacturability assessment of sheet metal parts is another important activity for die design. Traditional process of manufacturability assessment of sheet metal parts involves calculations and decisions, which have to be made on the basis of experience and practice codes without the computer aids. It is estimated that

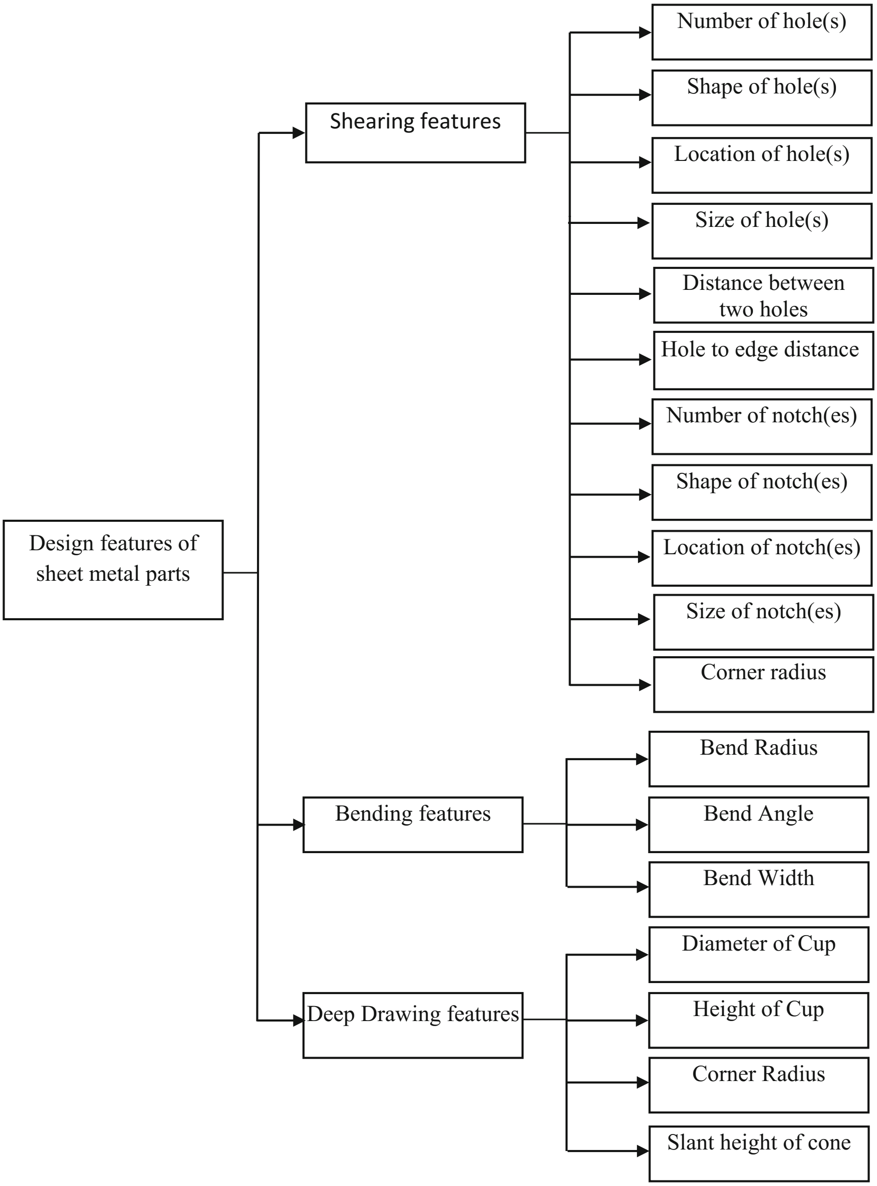


Fig. 2 Common design features of sheet metal parts

decisions made at the part design stage determine 70–80 % of the manufacturing productivity (Makinouchi 1996). Therefore, during the planning for manufacturing of a sheet metal part, it is useful to check its internal as well as external features for assessing its manufacturability on a press tool or die. Such checks are useful to avoid manufacturing defects, section weakness, and need of new dies, tools, or machines. Over the years the industrial practices of checking of the internal and external features of sheet metal parts have not changed significantly.

The present chapter describes a computer-aided system for automatic feature extraction of sheet metal parts and a knowledge-based system (KBS) for manufacturability assessment of sheet metal parts. The chapter is further organized as follows—The first section introduces feature extraction and manufacturability assessment of sheet metal parts. Next, the research efforts applied by worldwide researchers in the area of feature extraction and manufacturability assessment are reviewed. The third section describes a computer-aided system for automatic feature extraction of sheet metal parts. The next section presents a KBS for manufacturability assessment of sheet metal parts. In the fifth section, validation of developed systems of feature extraction and manufacturability assessment has been presented by taking three industrial sheet metal parts. Finally, the present chapter is summarized.

2 Literature Review

2.1 Feature Extraction/Recognition of Sheet Metal Parts

Feature recognition of sheet metal parts was given a new dimension in the late 1980s. Many researchers have worked on feature recognition of sheet metal parts. Meeran and Pratt (1993) developed a system for automatic feature recognition for simple prismatic part. The input is 2-D drawing of prismatic part in a DXF format. Liu et al. (2003) presented a method for automatic extraction of features from arbitrary solid model of sheet metal parts. The developed system is divided into three categories—checking of model geometry, feature matching, and setting feature relationship. Ismail et al. (2005) proposed a new technique for feature recognition from B-rep (Boundary Representation) models. This technique identifies solid and void 'sides' of a boundary entity, and extracts cylindrical-based and conical-based features. Emad et al. (2006) proposed an intelligent feature recognition methodology for automatic feature recognition of 3-D prismatic parts. They used solid modeling based on constructive solid geometry (CSG). Zhou et al. (2007) used feature recognition concept for integration of CAD and computer-aided process planning (CAPP). Developed system is capable to recognize features, feature tree reconstruction, technical information processing, and process planning. Sunil and Pande (2008) developed a system for automatic recognition of features from freeform surface CAD models of sheet metal parts represented in STL format.

Rameshbabu and Shunmugam (2009) presented a hybrid approach to recognize the manufacturing features from 3-D CAD model of STEP AP-203. Farsi and Arezoo (2009) described feature recognition model along with the design advisor system for sheet metal parts. They used commercial CAD software and user interface is created using visual basic (VB). Proposed model recognizes part features, such as bend radius, bend angle, length of each bend, bend height, bend direction, bend factor, and sheet thickness. Sunil et al. (2010) developed the new hybrid approach for recognizing the interacting feature from B-rep CAD model. Developed system recognizes all varieties of the simple and stepped holes with flat and conical bottoms from the feature graphs. Wang et al. (2012) proposed a feature recognition system to identify shape and size of different features from 3-D model of part. Tan et al. (2013) developed feature recognition system for integration of CAD and CAM. The CAD model in STEP format is used for recognition of holes on sheet metal part. Rule-based technique is used for development of feature recognition rules. Hussein and Kumar (2008) used STEP AP-203 CAD model for feature recognition of 3-D prismatic parts. The attribute adjacency graph (AAG) and attribute adjacency matrix (AAM) approaches have been used for recognition of assembly features. System can recognize both depression and protrusion features.

From review of available literature it is found that the worldwide researchers have applied efforts to develop computer-aided feature extraction/recognition systems for sheet metal parts. Most of the researchers have developed systems which are able to perform feature recognition only for simple part geometry. Also, most of these CAD systems uses semi-automatic approach and require expert persons to operate the systems and interpret the results. Very few systems have been developed for automatic feature extraction of sheet metal parts. Even these systems are not capable to recognize the complex and intersecting features from solid CAD model. In addition, these systems require high-performance computers for processing of algorithm and extraction of features.

2.2 *Manufacturability Assessment of Sheet Metal Parts*

Worldwide researchers have applied efforts to develop computer-aided systems for manufacturability assessment of sheet metal parts. For example, Nakahara et al. (1978) introduced a progressive die design system that examines the part design data to decide whether it can be stamped by blanking or not. The Cold Press Die Design and Manufacturing system (CPDDMS) developed by Ying (1986) manipulates the digital representation of blanks stored in data files to perform technology check of the blank geometry. But the main limitation of this system is that it is implemented on a main frame computer with advanced data base support and thus it is beyond the reach of the small and medium sized tool and die industries. Illiev et al. (1989) developed a system, which mainly addresses the technical preparation in the production of flat parts by stamping. The major limitation of this system is that it involves large number of mathematical calculations of the geometrical characteristics of the sheet metal part just like the traditional methods being used in industries. The Technology Check module of the computer-aided die design system (CADDS) proposed by Prasad and Somasundaram (1992) is capable of assessing the feasibility of sheet metal blank for the blanking process. Lazaro et al. (1993) developed an intelligent system labeled as SMART (Sheet Metal Advisor and Rule Tutor) for identifying design rule violations to improve part manufacturability. System consists of a feature-based CAD system and a knowledge-based system (KBS). Meerkamm (1995) proposed a design support system based on a data exchange format to detect design violations concerning manufacturability of sheet metal, rotational and casting parts, and to advise for correction. Lee et al. (1995) reported an assessment system consisting of knowledge-based geometric analysis module, a finite element module and a formability analysis module. The geometric analysis module uses geometric reasoning and feature recognition with a syntactic approach to extract high-level geometric entity information from vertices in two-dimensional forming. Yeh et al. (1996) developed a rule-based and feature-based design advisor for sheet metal parts called product modeler (ProMod-S), which includes a rule-based design advisor among several other modules. An advisory design rule checker system was proposed by Radhakrishnan et al. (1996). This system is integrated into ProMod-S using medial axis transformation algorithm to check the number of features for complicated sheet metal parts. Wang and Bourne (1997) described a manufacturability-driven decomposition approach to decompose bent sheet metal products into manufacturable parts. Choi and Kim (2001) developed a CAD/CAM system for the blanking or piercing of irregular shaped-sheet metal products for progressive working. The system is capable of checking the production feasibility of parts using AutoLISP and Auto CAD. But this system is limited to stator and rotor parts which require only blanking or piercing operations. Tang et al. (2001) proposed an intelligent feature-based design system for stampability evaluation of a sheet metal part for checking of potential problems in stamping process and stamping die at the design stage itself. Ramana and Rao (2005) developed a system for automated manufacturability evaluation of sheet metal parts. The system describes design evaluation, process planning, data, and knowledge modeling for shearing and bending operations. Scope of the system is limited to simple bending parts only and those parts which can be produced by blanking and piercing operations. Kumar et al. (2006) developed a knowledge-based system (KBS) for checking design features of sheet metal parts to be manufactured on progressive die. Farsi and Arezoo (2009) proposed a system based on object-oriented approach. This system includes two modules: feature recognizer and design for manufacturability module. The system can recognize incorrect features and imparts suggestions for editing incorrect features. Naranje and Kumar (2011) proposed a KBS for manufacturability assessment of deep drawn sheet metal parts. Production rules are coded in AutoLISP language. Graphical user interface is created using Visual Basic (VB) and interfaced with AutoCAD software. Kashid and Kumar (2013) developed a system for manufacturability assessment of parts produced on compound dies.

From the reviewed literature it is found that some researchers have developed specific systems for manufacturability assessment of sheet metal parts using CAD and artificial techniques (AI) techniques. But no system is available to deal with all types of sheet metal parts comprising shearing, bending and deep drawing features.

3 Computer-Aided System for Automatic Feature Extraction

A computer-aided system labeled as FE (*F*eature *E*xtraction) has been developed for automatic feature extraction of sheet metal parts. This system is generic in nature and derives information from the topology, geometry, and Boolean logic. The system has been coded in AutoLISP language. Execution of the proposed system is shown in Fig. 3. Initially, the system invites the user to enter input in form of 3-D CAD drawing of sheet metal part in AutoCAD software. This drawing file is saved as BLKMOD.DWG for its further use. The system extracts design features in two stages—(i) prefeature extraction, and (ii) feature extraction. In prefeature extraction stage, faces of the 3-D CAD drawing file of sheet metal part are exploded. The AutoCAD command 'EXPLODE' is used for identifying features present on sheet metal part. In the second stage, features of sheet metal part are extracted automatically by the proposed system. These extracted features are displayed to the user and stored automatically in a data file labeled as FE.DAT. This output data file acts as an input to the subsequent modules of die design automation systems.

4 Knowledge-Based System for Manufacturability Assessment of Sheet Metal Parts

The external and internal design features of the part such as size of blank, width of recesses or slots or projections along blank profile, dimension and location of holes, internal contours, distance of internal features from the edge of blank, draw ratio, bend angle, bend radius, bend width, size and position of hole/slot, and direction of bend should be tested against rules of good practice. Most of the sheet metal industries use internal guidelines for part design based on the experience with the part geometry and materials used in that specific company. While such design guidelines are extremely useful and practical but they do not necessarily consider the fundamental reasons for selecting a given design. Thus, when a new material is introduced the entire set of experienced-based design guidelines must be reevaluated and modified. Therefore, it is necessary to develop generic design guidelines

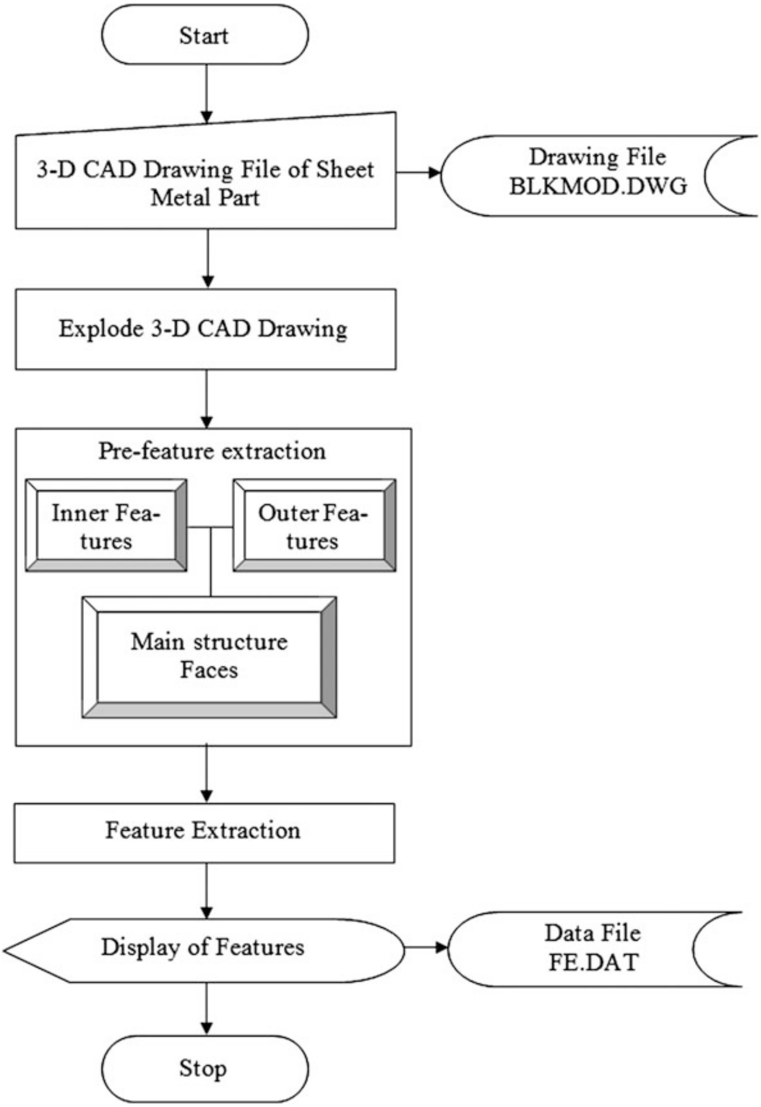


Fig. 3 Execution of FE system

based on metal forming analysis and/or systematic experimental investigation. Figure 4 shows the design guidelines for deep drawn parts used in automotive industries (Suh 1988). Figure 5 shows a sample of design guidelines for bending parts.

Experienced die designers and process planners generally use some basic guidelines to assess manufacturability of sheet metal parts. A sample of these basic

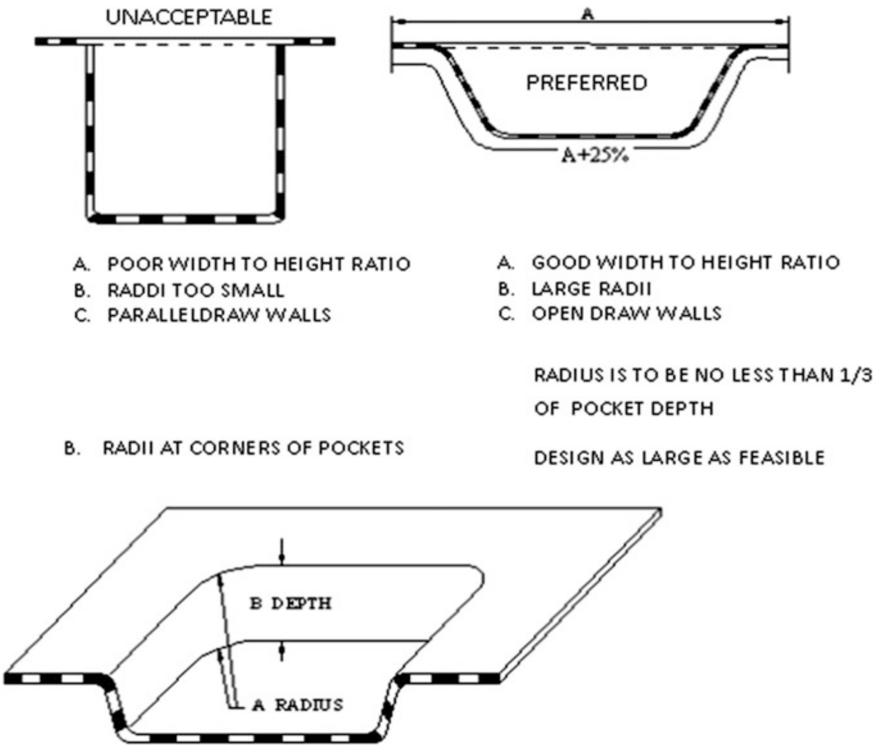


Fig. 4 Design guidelines for sheet metal parts used in automotive industry (Suh 1988)

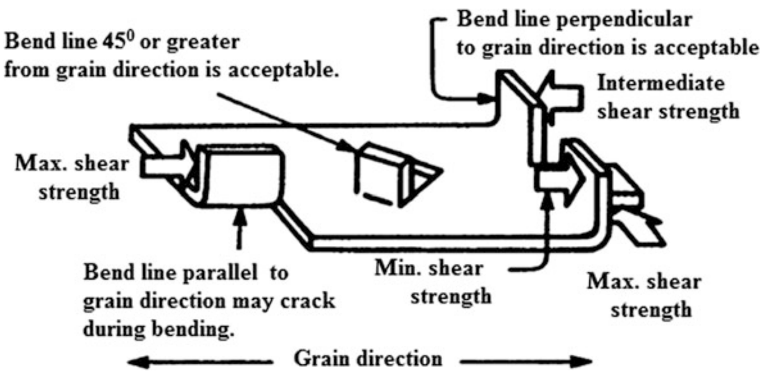


Fig. 5 A sample of design guidelines for bending parts (Farsi and Arezoo 2009)

guidelines is given as under (Kumar et al. 2006; Naranje and Kumar 2011, 2014; Kashid and Kumar 2013):

(1) The minimum width of sheet metal part is a function of sheet thickness. It is very difficult to design and manufacture dies for long and narrow parts. The width of parts should not be less than 1.5 times of sheet thickness and length should not be greater than five times of width of blank.
(2) The corner radius on sheet metal parts should be at least 0.7 times of sheet thickness.
(3) The width of recesses or slots or projections along blank profile should be minimum 1.2 mm.
(4) The permissible minimum diameter of piercing depends on the type of sheet material, shape of holes and sheet thickness. For piercing round holes, the diameter should not be less than 0.5 mm for hard steel sheet material and 0.4 mm for soft steel, brass or aluminium sheet material. The size of a square or rectangular hole should not be less than 0.35 mm for soft steel, brass, or aluminium sheet material.
(5) The spacing between holes on sheet metal parts should be at least 2.0 times of sheet thickness.
(6) The distance between the two nearest internal features influences the ease of manufacturing and the construction of die. The minimum allowable spacing between two internal features depends on the thickness, hardness of sheet material and shape of feature.
(7) The maximum length of a rectangular/radial notch is generally taken as 5.0 times of width of notch. The maximum length for a 'V'-notch is recommended as 2.0 times of width of notch.
(8) Scrap web allowance depends on the maximum product size, sheet thickness and shape of product edge.
(9) Higher thickness to diameter ratio of deep drawn parts is good and it should be at least one percent. If it is less then wrinkling may occur.
(10) Depth and length of the deep drawn parts must be greater than one half of their diameter.
(11) Sharp radius (inside radius or flange radius) should be avoided.
(12) With a large radius of the drawing die ranging between 8 to 15 times of sheet thickness, smaller values of the severity of the draw coefficient may be used. Subsequently, with smaller drawing die radii such as those ranging between 4 to 8 times of sheet thickness, larger draw coefficient is recommended.
(13) When the draw radius is too small, excessive thinning or fracture results at the bottom of a shell and at any stage of the operation. This can be corrected by increasing die radius or blank diameter to allow easier metal flow.
(14) Suitability of drawing material should be evaluated on the basis of its coefficient of normal anisotropy.

(15) Large draw ratios imply long and thin forming punches that tend to be very susceptible to breakage. This increases the maintenance cost of deep drawing die.
(16) The value of deformation should be within 25–75 % of the value of drawability.
(17) Vertical axis of blank should be exactly in line with the axis of punch and die during the deep drawing operation.
(18) For rectangular part, draw depth should be limited to 7 times of corner radius.
(19) Included corner angle less than 60° reduces feasible depth of draw.
(20) For rectangular part, both the draw and vertical corner radii must be 5 times of sheet thickness.
(21) Maximum possible bend angle in a bending part depends on sheet material, sheet thickness, and bend radius.
(22) The minimum bend radius of a bend depends on sheet material and sheet thickness.
(23) The bend width should be at least three times of sheet thickness.
(24) The minimum acceptable bend length of a bend depends on the sheet thickness and bend radius. It should not be less than 2.5 times of sum of sheet thickness and bend radius.
(25) The bend should be perpendicular to the grain direction or as close as possible in order to avoid fracture of the part.
(26) The mutually perpendicular bends should be made at 45° to the grain direction.
(27) The minimum acceptable distance of edge of hole/slot from the nearest edge of bending part depends on sheet thickness and bend radius. It should not be less than 1.5 times of the sum of sheet thickness and bend radius.
(28) If it is not possible (as per the functional requirement of part) to follow the minimum acceptable distance criteria as mentioned above, then a stress discontinuity should be provided by a nonfunctional hole/slot/tab to prevent the distortion of hole.
(29) If the hole(s) or slot(s) is/are on a bend line then such feature(s) should be formed after bending.
(30) Dimensional tolerances less than 0.04 mm is very difficult to maintain and a costly affair.

Keeping in view of the above basic guidelines, a KBS labeled as MCKBS (*M*anufacturability *C*heck *K*nowledge-*B*ased *S*ystem) is developed for assessing manufacturability of sheet metal parts at initial stage of design. The system is described as under.

4.1 Procedure for Development of the Proposed System

The procedural steps for the development of the proposed system namely MCKBS include knowledge acquisition, framing and verification of production rules, sequencing of production rules, development of knowledge base, choice of search strategy, and preparation of user interface (Kumar and Singh 2004, 2011; Kumar 2011). Technical knowledge has been acquired from various sources including consultation with experienced die designers, process planers and shop floor engineers, review of published research papers, die design handbooks, industrial brochures, and technical reports. The knowledge thus acquired is analyzed and tabulated in form of production rules of 'IF–THEN' variety. The production rules so framed are verified from a team of domain experts. Production rules are arranged in a structured manner. Suitable software should be selected for development of a knowledge base system As the AutoCAD software has low cost, therefore it can be easily affordable by small scale sheet metal industries. Further, to make user-interactive expert system, visual basic (VB) software is always preferred. The proposed system is implemented using VB and AutoCAD software. To develop knowledge base of the proposed system, production rules are coded in AutoLISP language and graphical user interface (GUI) is created using VB software. The production rules and the knowledge base of the system are linked together by an inference mechanism, which makes use of forward chaining. The system works with input information supplied by the user coupled with knowledge stored in the knowledge base, to draw conclusions or recommendations. The developed system MCKBS overall comprises of more than 800 production rules of IF-THEN variety. A sample of production rules incorporated in the knowledge base of proposed system is given in Table 1.

The user initially loads the system by using graphical user interface (GUI). Proposed system automatically recalls data file labeled as FE.DAT which is generated during execution of feature extraction system. The system also invites the user to enter part data information such as sheet material and production quantity through GUI. The system stores these part data in a data file labeled as PD.DAT. Thereafter, the system checks various design features of sheet metal part from manufacturability point of view. If any design feature(s) of part, such as size of holes, distance between hole(s) and strip edge, distance between two holes, size of notch(es), corner radius, bend angle, bend radius, bend width, size and position of hole/slot, and direction of bend (in case of bending parts), thickness ratio, height ratio, draw radii, draw ratio, etc. (in case of deep drawn parts) is/are not in accordance to the good design practice, the system suggests the user for necessary design modifications. Lastly, the system displays advices for necessary scrap web allowance for manufacturing sheet metal part and stores this output in a data file labeled as SWA.DAT.

Table 1 Production rules included in the system MCKBS

S. No.	IF	THEN
1	Width of blank < 1.5 times sheet thickness	Set minimum width of blank = 1.5 times sheet thickness
2	Length of blank > 5.0 times of width of blank	Set maximum length of blank = 5.0 times of width of blank
3	Width of recesses or slots or projections along blank profile ≥ 1.2 mm	Accept width of recesses or slots or projections
4	Sheet material = Tin/Copper/Brass/Stainless steel/Aluminum; and Design feature = Circular hole; and 0.5 mm ≤ minimum hole diameter ≥ 1.3 times of sheet thickness	Accept the diameter of circular hole
6	Minimum distance between two holes on sheet metal part in mm ≥ 2.0 times of sheet thickness	Accept the minimum spacing between two holes on sheet metal part
7	Design feature = Rectangular notch; and Width of rectangular notch in mm ≥ 1.5 times of sheet thickness	Accept the width of rectangular notch
8	Design feature = Rectangular notch; and Length of rectangular notch in mm ≥ 5.0 times of sheet thickness	Accept the length of rectangular notch
9	Minimum internal or external corner radius on sheet metal part in mm ≥ 0.9 times of sheet thickness	Accept the corner radius on sheet metal part
10	Minimum distance of edge to hole in mm < 2.0 times of sheet thickness	Set minimum distance of edge to hole = 2.0 times of sheet thickness
11	Part material = Steel annealed; and Bend radius ≤ two times of sheet thickness; and 0° < Angle between bend axis and grain direction ≤ 45°; and 0° < Bend angle ≤ 135°	Accept the bend radius
12	Part material = Steel annealed; and Bend radius ≤ two times of sheet thickness; and 0° < Angle between bend axis and grain direction ≤ 45°; and 135° < Bend angle ≤ 180°	Set the bend radius ≥ two times of sheet thickness, 'OR' Set the bend angle < 135°, 'OR' Set angle between bend axis and grain direction > 45°
13	Part material = Steel annealed; and bend radius ≤ two times of sheet thickness; and 45° < Angle between bend axis and grain direction ≤ 90°; and 90° < Bend angle ≤ 180°	Accept the bend radius
14	Part material = Steel annealed; and two times of sheet thickness < Bend Radius ≤ four times of sheet thickness; and 0° < Angle between bend axis and grain direction ≤ 45°; and 0° < Bend angle ≤ 180°	Accept the bend radius

(continued)

Table 1 (continued)

S. No.	IF	THEN
15	Part material = Steel annealed; and Two times of sheet thickness < Bend radius ≤ four times of sheet thickness; and 45° < angle between bend axis and grain direction ≤ 90°; and 0° < Bend angle ≤ 180°	Accept the bend radius
16	Part material = steel annealed; and Bend Radius > four times of sheet thickness; and 45° < angle between bend axis and grain direction ≤ 90°; and 0° < Bend angle ≤ 180°	Accept the bend radius
17	Part material = Steel Annealed; and Minimum bend radius < 0.5 times of sheet thickness	Set the minimum bend radius = 0.5 times of sheet thickness
18	Part material = Cu ETP; and Minimum bend Radius < 0.25 times of sheet thickness	Set the minimum bend radius = 0.25 times of sheet thickness
19	Ratio of flange diameter to cup diameter < 1.1; and 0.002 ≤ Ratio of sheet thickness to blank diameter < 0.005	Set the ratio of cup height to cup diameter ≤ 0.60
20	Ratio of flange diameter to cup diameter < 1.1; and 0.005 ≤ Ratio of sheet thickness to blank diameter < 0.01	Set the ratio of cup height to cup diameter ≤ 0.68
21	1.1 ≤ Ratio of flange diameter to cup diameter < 1.3; and 0.01 ≤ Ratio of sheet thickness to blank diameter < 0.015	Set the ratio of cup height to cup diameter ≤ 0.70
22	1.3 ≤ Ratio of flange diameter to cup diameter < 1.5; and 0.0006 ≤ Ratio of sheet thickness to blank diameter < 0.002	Set the ratio of cup height to cup diameter ≤ 0.40
23	1.5 ≤ Ratio of flange diameter to cup diameter < 1.8; and Ratio of sheet thickness to blank diameter > 0.015	Set the ratio of cup height to cup diameter ≤ 0.56
24	Sheet material = Extra deep drawing steel; and 0.0008 ≤ Ratio of sheet thickness to blank diameter < 0.0015; and Draw stage = First	Set limiting draw rate ≤ 0.63
25	Sheet material = Extra deep drawing steel; and 0.0008 ≤ Ratio of sheet thickness to blank diameter < 0.0015; and Draw stage = Second	Set limiting draw rate ≤ 0.82
26	Sheet material = Extra deep drawing steel; and 0.0008 ≤ Ratio of sheet thickness to blank diameter < 0.0015; and Draw stage = Third	Set limiting draw rate ≤ 0.84

(continued)

Table 1 (continued)

S. No.	IF	THEN
27	Sheet material = Extra deep drawing steel; and 0.0015 ≤ Ratio of sheet thickness to blank diameter < 0.0030; and Draw stage = First	Set limiting draw rate ≤ 0.60
28	Sheet material = Extra deep drawing steel; and 0.0015 ≤ Ratio of sheet thickness to blank diameter < 0.0030; and Draw stage = Second	Set limiting draw rate ≤ 0.80
29	Sheet material = Extra deep drawing steel; and 0.0015 ≤ Ratio of sheet thickness to blank diameter < 0.0030; and Draw stage = Third	Set limiting draw rate ≤ 0.82
30	Sheet material = Extra deep drawing steel; and 0.0030 ≤ Ratio of sheet thickness to blank diameter < 0.0060; and Draw stage = First	Set limiting draw rate ≤ 0.58
31	Sheet material = Extra deep drawing steel; and 0.0030 ≤ Ratio of sheet thickness to blank diameter < 0.0060; and Draw stage = Fifth	Set limiting draw rate ≤ 0.86
32	Sheet material = Extra deep drawing steel; and 0.015 ≤ Ratio of sheet thickness to blank diameter < 0.020; and Draw stage = Second	Set limiting draw rate ≤ 0.75
33	Cup geometry = Cylindrical; and 0.75 < Height to diameter ratio ≥ 1.50; and Number of drawing stages = 2	Set percentage reduction for First draw = 40 %; and Second draw = 25 %
34	Cup geometry = Cylindrical; and 0.75 < Height to diameter ratio ≥ 1.50; and Number of drawing stages = 3	Set percentage reduction for First draw = 40 %; Second draw = 25 %; and Third draw = 15 %
35	Cup geometry = Cylindrical; and 0.75 < Height to diameter ratio ≥ 1.50; and Number of drawing stages = 4	Set percentage reduction for First draw = 40 %; Second draw = 25 %; Third draw = 15 %; and Fourth draw = 10 %
36	Sheet material = Extra deep drawing steel; and Ratio of flange diameter to cup diameter ≤ 1.1	0.0006 ≤ Set the thickness ratio > 0.02
37	Sheet material = Extra deep drawing steel; and 1.1 < Ratio of flange diameter to cup diameter ≤ 1.3	0.002 ≤ Set the thickness ratio > 0.005

(continued)

Table 1 (continued)

S. No.	IF	THEN
38	Product size (maximum length/diameter/width) in mm > 25.0 mm; and Product size (maximum length/diameter/width) in mm ≤ 75.0 mm; and Sheet thickness in mm < 1.5; and Shape of product edge = Straight or parallel edge	Set minimum scrap web allowance in mm = 1.5 times of sheet thickness
39	Product size (maximum length/diameter/width) in mm > 75.0 mm; and Product size (maximum length/diameter/width) in mm ≤ 150.0 mm; and Sheet thickness in mm < 1.5; and Shape of product edge = Straight or parallel edge	Set minimum scrap web allowance in mm = 1.6
40	Product size in mm (maximum diameter/length/width) ≤ 25, and Sheet thickness ≥ 1.2 mm, and Shape of product edge = curved	Set scrap web allowance in mm = sheet thickness
41	Product size in mm (maximum diameter/length/width) ≤ 25 and Sheet thickness < 1.2 mm, and Shape of product edge = curved	Set minimum scrap web allowance in mm = 1.2
42	25 < Product size in mm (maximum diameter/length/width) ≤ 75, and Sheet thickness ≥ 1.3 mm and Shape of product edge = curved	Set scrap web allowance in mm = 1.25 times of sheet thickness
43	25 < Product size in mm (maximum of diameter, length & width) ≤ 75, and Sheet thickness < 1.3 mm, and Shape of product edge = curved	Set minimum scrap web allowance in mm = 1.6
44	250 < Product size in mm (maximum diameter/length/width) ≤ 400, and Sheet thickness ≥ 2.3 mm, and Shape of product edge = curved	Set scrap web allowance in mm = 1.75 times of sheet thickness

5 Validation of the Proposed Systems FE and MCKBS

The proposed systems have been tested on various types of sheet metal parts. The output generated by the systems FE and MCKBS for three industrial sheet metal parts (Figs. 6, 7 and 8) taken from sheet metal industries namely M/s Indo-German Tool Room, Aurangabad, India, M/s D. D. Engineering Pvt. Ltd., Pune, India, and M/s Kochar Agro Industries Pvt. Ltd. Faridabad, India respectively are depicted in Figs. 9, 10, 11, 12, 13, 14, 15 and 16. The features extracted automatically by the system FE are verified from the CAD drawings of example sheet metal parts. Also, the recommendations/expert advices imparted by the system MCKBS are found to be reasonable and very similar to those actually used in the said industries for the example parts.

Sheet material = Stainless Steel [AISI 1090]
Sheet thickness = 0.5mm

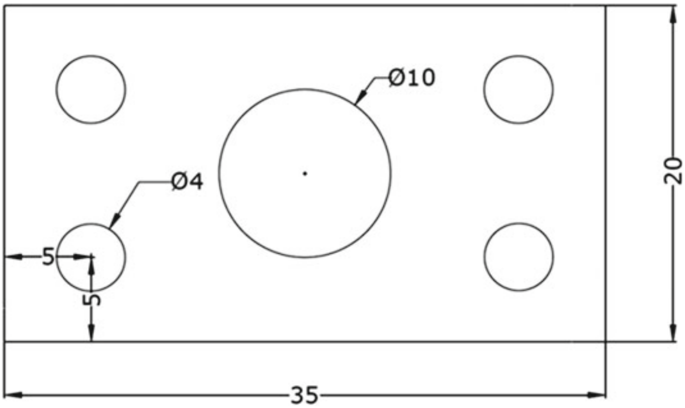


Fig. 6 Example part 1 (All dimensions are in mm) (M/s Indo-German Tool Room, Aurangabad, India)

Sheet material = Stainless Steel [AISI 1090]
Sheet thickness = 0.8mm

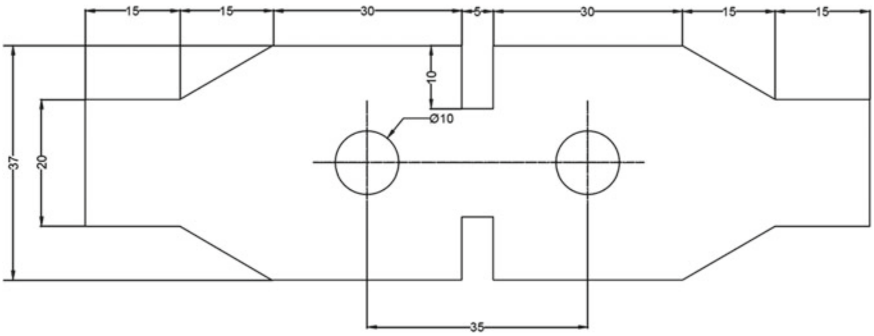
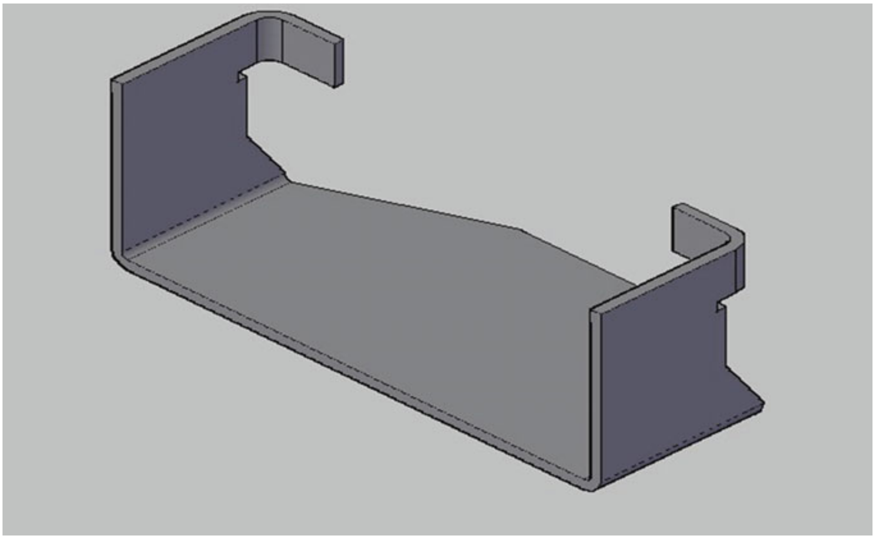
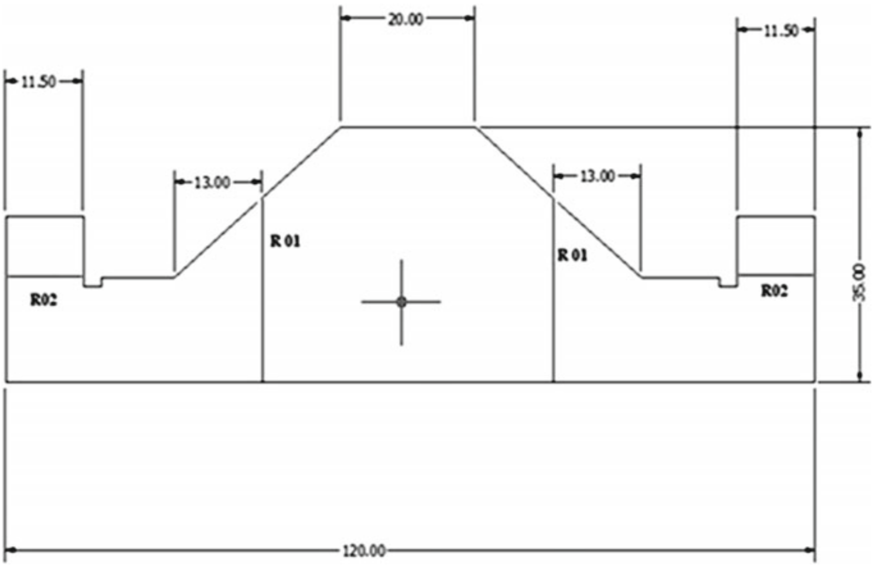


Fig. 7 Example part 2 (All dimensions are in mm) (M/s D. D. Engineering Pvt. Ltd., Pune, India)



(a) 3-D View



Material = Low Carbon Steel Hardened
Sheet thickness = 1.5 mm

(b) 2-D View

Fig. 8 Example part 3 (All dimensions are in mm) (M/S Kochar Agro Industries Pvt. Ltd. Faridabad, India)

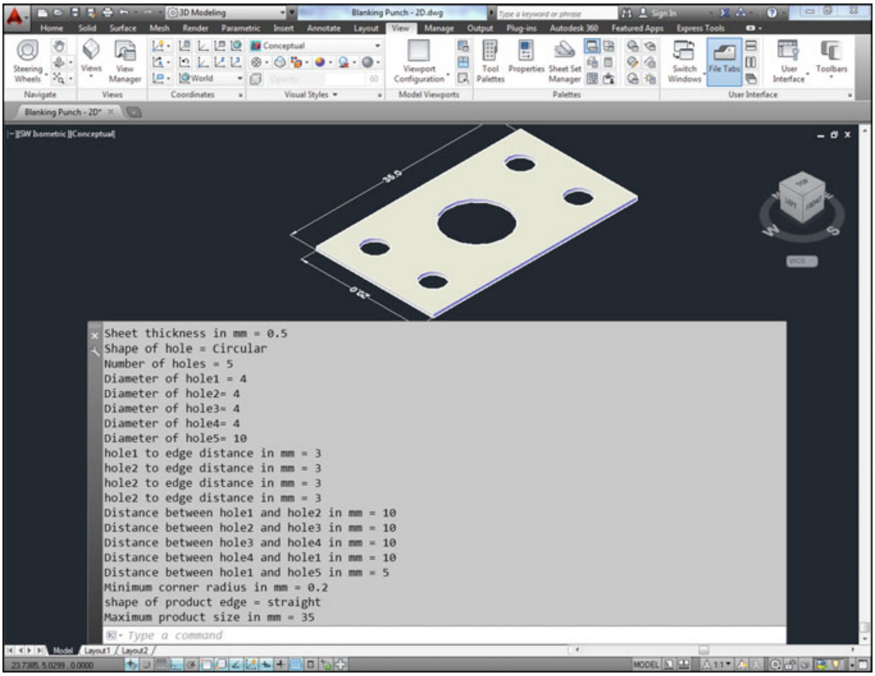


Fig. 9 Output of system FE for example part 1

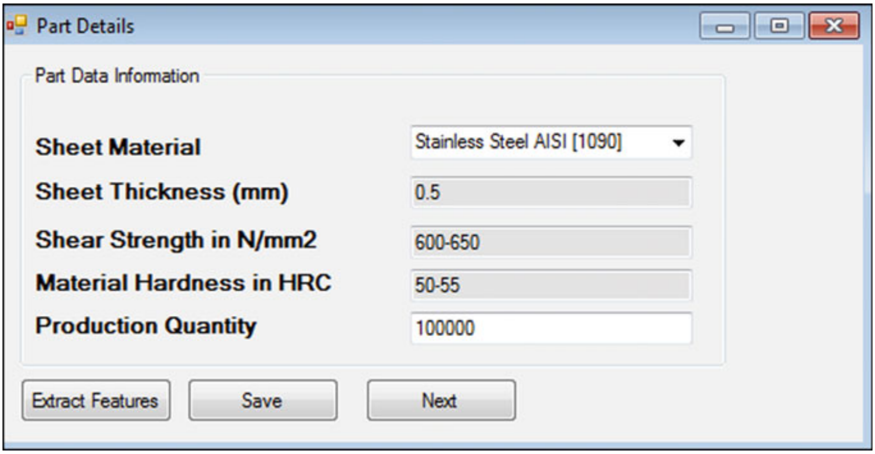


Fig. 10 Input data for MCKBS for example part 1

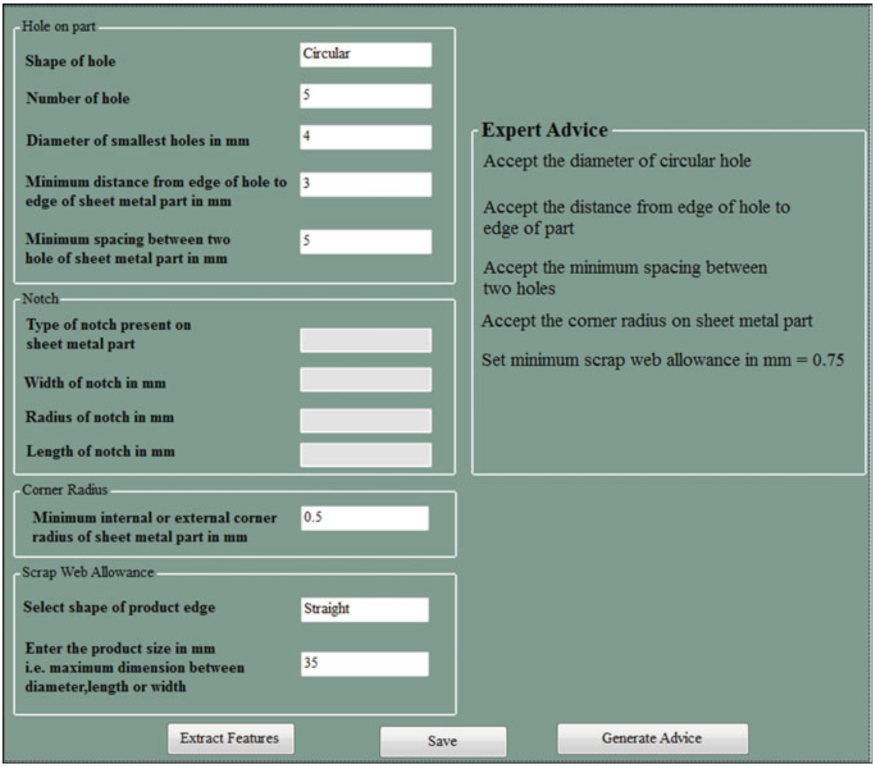


Fig. 11 Output of MCKBS for example part 1

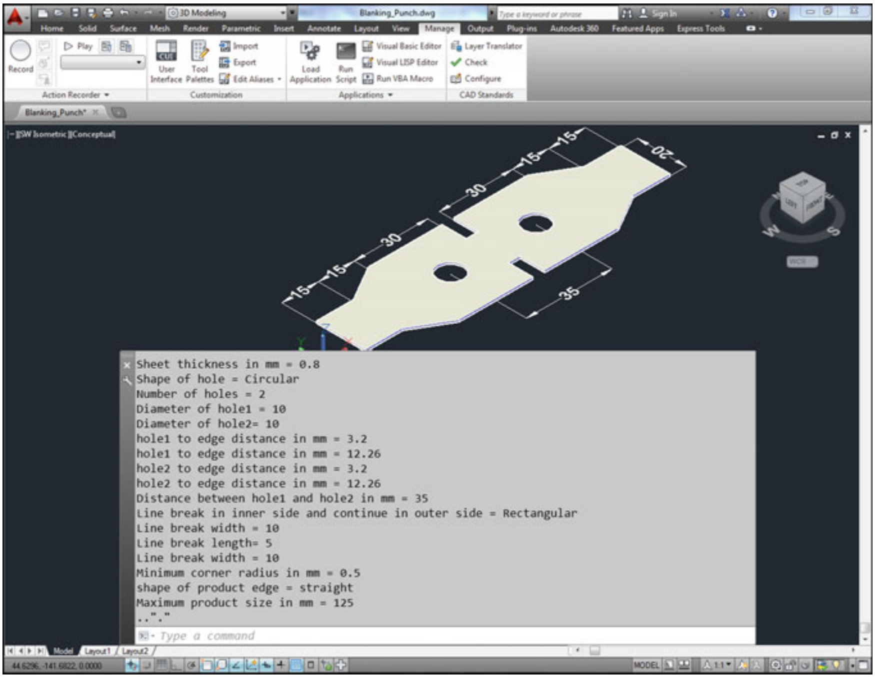


Fig. 12 Output of system FE for example part 2

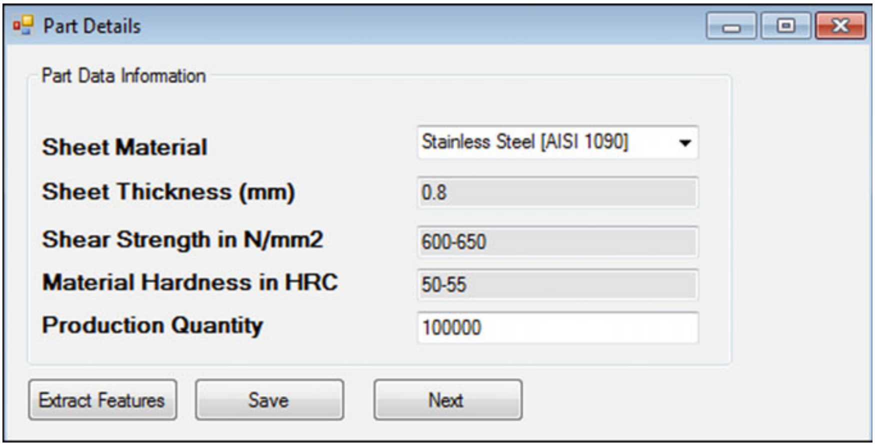


Fig. 13 Input data for MCKBS for example part 2

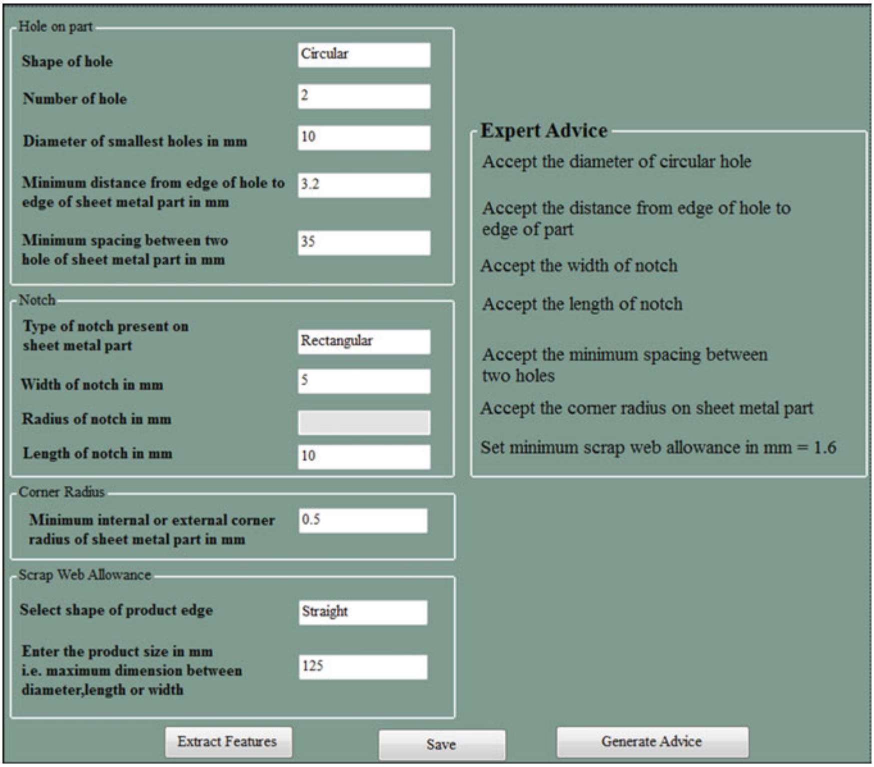


Fig. 14 Output of MCKBS for example part 2

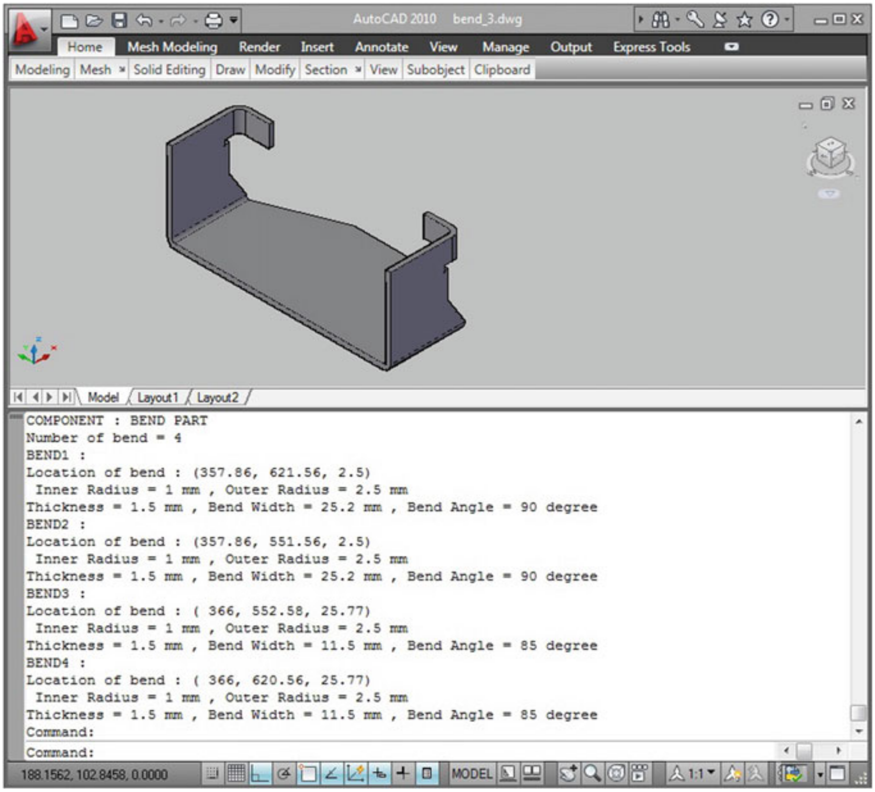
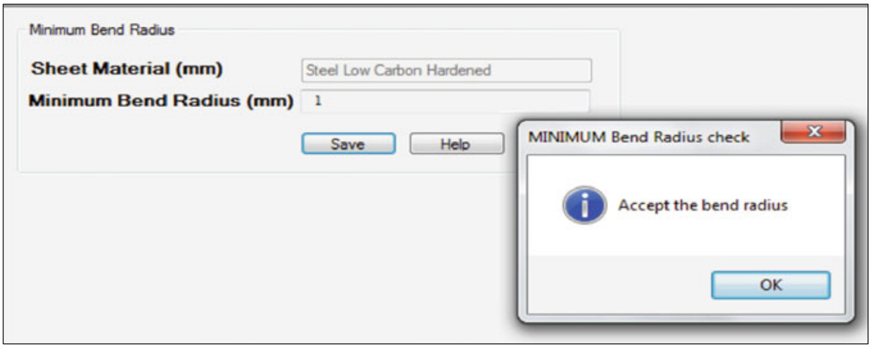
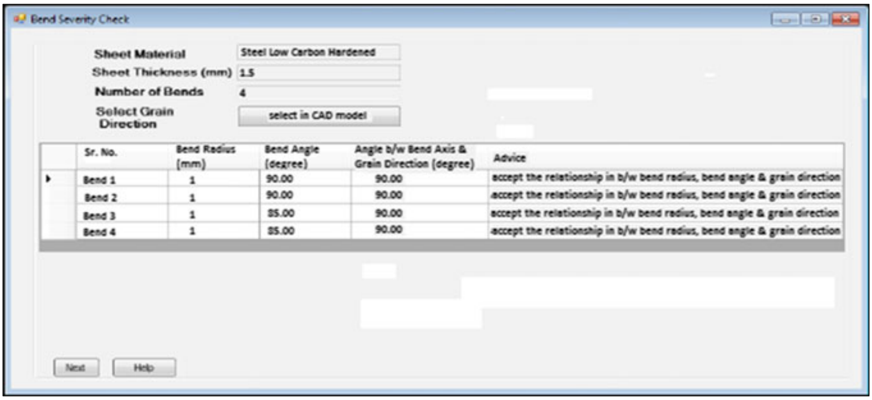


Fig. 15 Output of system FE for example part 3



(a) Check for bend radius



(b) Check for bend severity

Fig. 16 Output of MCKBS for example part 3

6 Conclusion

Feature extraction and manufacturability assessment of sheet metal parts are essential requirements for development of knowledge-based system (KBS) for design of press tools. The present chapter described the work involved in development of computer-aided system for feature extraction and a KBS for manufacturability assessment of sheet metal parts. The usefulness of the proposed systems is demonstrated on three sheet metal parts of different industries. The outputs imparted by these systems are stored in different data files, which are further used in design of different types of dies as described in subsequent chapters.

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Knowledge-Based System for Design of Blanking Dies

Hussein M.A. Hussein, Azza F. Barakat, Wang Fengyin and Shailendra Kumar

1 Introduction

Blanking die is a single station cutting die which deals with regular-and irregular-shaped sheet metal parts. It is usually used in the first operation for cutting off the blank when the sheet metal part is manufactured in a serious of stamping operations. This makes blanking dies (design and manufacturing) an important tool in sheet metal industries. Although blanking dies seem to be a simple type of die, yet its design process is complex and requires highly experienced persons. There is a variety of shapes of blanking dies to produce different types of sheet metal parts with different sizes, shapes, thicknesses, designs, and material types. Classification and coding of sheet metal blanking dies can be a good step for knowing the relation between die part shapes and die shapes. In this chapter, a new classification is proposed. Blanking die types are classified into two main groups—fixed and movable stripper types. Each group can be further classified, according to its size (i.e. small, small–medium, medium, medium large, large, and extra-large sizes). Each size has its own design characteristics based on the added or removed

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components in its classification skeleton. In fact, optimum design is a tool for finding out the most suitable size of die.

Computer-aided selection of type of blanking dies that directs to optimum solution, has not been reported so far in the available literature. It may be the first time herein to study this idea. This type of research can result in a fully automated die design system using knowledge-based approach and artificial intelligence (AI). The computer-aided design and drafting of sheet metal blanking die involves two main tasks. The first one is the development of the knowledge-base (KB) for die design; and the second is the parametric design functions.

Research efforts made in the area of computer-aided die design mainly concentrated on describing a specific size of blanking dies. For example, Ruan et al. (1987) developed a blanking CAD system called “SBDS.” Prasad and Somasundaram (1991, 1992) proposed two systems “CASNS” for sheet metal nesting, and “CADDS” for sheet metal blanking dies. The proposed systems were for progressive die. Wong (1992) described a system called BECAM which is suitable for medium sized dies. Huang et al. (1993) constructed a Computer-Aided Press-Tool Design “CAPTD.” It deals with small blanking dies. Choi et al. (1998) discussed a compact CAD/CAM system for blanking die. Nye (1999) proposed a technique for sheet metal nesting for blanking dies. Hussein et al. (1999) constructed JUPITER’99 which is used only for medium-large size blanking dies. Pacanowski (2000) discussed a computer-aided design of the lower shedders used in blanking dies. Singh and Sekhon (2003) reported a special package called AUDIEDR which is suitable for small–medium type blanking dies. Also, Gürün et al. (2006) proposed two systems for strip layout and die design using Visual Lisp and VBA. Shaikh and Desai (2006) used Inventor as platform for blanking dies. Researchers Zamzam et al. (1988) and Bedewy et al. (1993), from Egypt have also contributed in the domain of blanking die design. In the domain of KBS/expert System for blanking die design, Akira (1982) described many shapes and classifications in blanking die designs. Lin et al. (1989) developed a system namely “ESSCP” for design of a simple blanking die shape. Zhao et al. (2001) discussed application of hybrid expert system in blanking process. Cheung (2001) reported a simple blanking die CAD using knowledge-based design. Recently, Sun and Song (2014) developed a KBS for blanking dies.

In fact, there is no system available till now to deal with all types and sizes of blanking dies. Rather, the existing systems are suited only for specific shape and size of blanked part. Therefore, it is meaningful to develop a computer-aided system for automated design of blanking dies for all types of stampings.

In this chapter, the functions of the KBS for designing blanking dies are first introduced. The sheet metal parts are analyzed by using methodologies, such as rule-based reasoning (RBR), which is the most widely used for solving such type of problems. The input parameters for the sheet metal part are thickness, diameter, length, width, contour length, area, the degree of accuracy, and quantity of parts to be produced per month. The output of KBS is in form of a digital number that gives an optimum design code. The system includes 60 case studies which are taken from actual and practical die design data base of reputed automotive manufacturers. The construction of the proposed system depends on three main programs—AutoCAD for solid modeling, MS-Access as a database for storing part data, and visual basic used as a design interface controller. The parametric functions control all the dimensions of die components with each other. It must be noted that the AutoCAD software does not support parametric technique, just like CATIA, Pro-Engineer, Inventor, SolidWorks, and the other recent CAD systems. In the present study, the parametric techniques under AutoCAD are customized as a tailor-made for blanking die design. The main purpose of using this technique is to automate design of blanking die.

2 Knowledge-Based Design Rules for Blanking Dies

In this section, the parameters of sheet metal parts are described for optimum designs of the sizes of the sheet metal blanking dies. The parts may have holes or bends but these design features are not considered in the present study.

2.1 Strip Thickness

Strip thickness is considered as the first parameter to be checked. It decides the main construction of die based on the type of the stripper. Listed in Table 1 are two rules for the classification of die type based on strip thickness.

2.2 Contour Length

The second parameter, contour length leads to the optimum size of die-block shape. Die block is the main component of a blanking die. The problem is that the contour length cannot alone lead to the correct die-block shape. For one specific contour length there can be numerous shapes. Those different part shapes (the same contour length with different dimensions) will determine the shape of the die block. To simplify this problem, there is a need to merge the parameters of part dimensions and contour length, in order to select the optimum design of the die block.

Table 1 Rules for selection of blanking die

Rules	Premises	Conclusions
1	Strip thickness (1–6 mm)	Use blanking die with fixed stripper
2	Strip thickness (0.5–1 mm)	Use blanking die with movable stripper

2.3 Main Part Dimension (Length/Width/Diameter)

Since sheet metal parts may have different shapes but approximately the same perimeter, the contour length itself will not lead to the optimum die block shape. Figure 1 shows four parts with different external shapes having approximately the same perimeter. Therefore, for each part shape, different die block is to be designed. The part dimensions alongside with the perimeter will lead to the selection of an optimum die block shape.

To simplify this problem, the contour length of blank part shape is converted into a diameter by dividing it by π. The empirical relationship between the diameter and the corresponding die block shape is given in Tables 2 and 3. The die sizes are

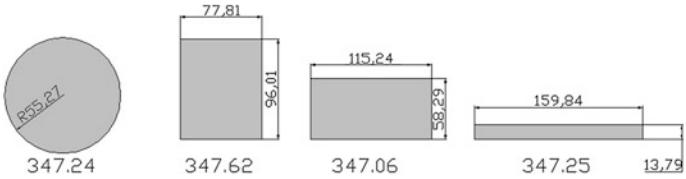


Fig. 1 Different shapes with the same perimeter length

Table 2 In case of blanking die—fixed stripper type

Premises	Conclusions
Diameter up to 100 mm	Select small size die (D01), circular die block insert
Diameter (100–125) mm	Select small–medium size die (D02), rectangular die block insert
Diameter (125–150) mm	Select medium size die (D03)
In Case of D01, D02 and D03: If part length or part width > diameter	Select medium-large size die (D04)
In Case of D01, D02 and D03: If part shape includes critical zones	Select medium-large size die (D07) with ejector
Diameter (150–250)	Select large size die (D05) Die-set of 2 column, die opening, segmentation die block
Diameter more than 250 mm	Select extra-large size die (D06). Die-set of 4 column, Ejector, segmentation die block
If part width per part length is less than 0.33 and if contour length is more than 250 mm and if Part thickness (3–6) mm	Select large size dies (D05)

Table 3 In case of blanking die—movable stripper type

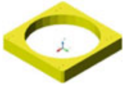
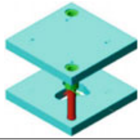
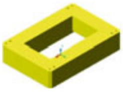
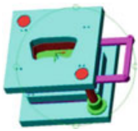
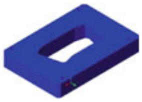
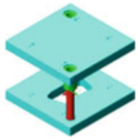
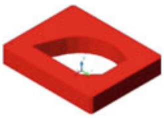
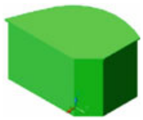
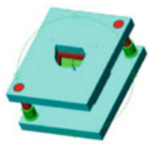
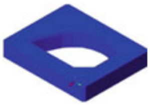
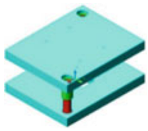
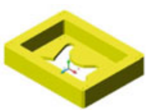
Premises	Conclusions
Diameter up to 100 mm	Select small size die (D08), circular die block insert
Diameter (100–125) mm	Select small–medium size die (D09), rectangular die block insert
Diameter (125–150) mm	Select medium size die (D10)
In Case of D01, D02 and D03) If part length or part width > diameter	Select medium-large size die (D11)
In Case of D01, D02 and D03) If part shape includes critical zones	Select medium-large size die (D14) with ejector
Diameter (150–250)	Select large size die (D12) Die-set of 2 column, die opening, segmentation die block
Diameter more than 250 mm, and thickness (0.25–1) mm	Select extra-large size die (D13) Die-set of 4 column, ejector, segmentation die block

classified into 14 different sizes, 7 sizes with fixed stripper and the other 7 sizes with movable stripper. For both the groups, dies are coded as follows.

(i) Small-size die with fixed stripper—D01,
(ii) Small–medium die size with fixed stripper—D02, and so on.
(iii) Medium size with fixed stripper—D03,
(iv) Medium-large size with fixed stripper—D04,
(v) Large size with fixed stripper—D05,
(vi) Extra-large size with fixed stripper—D06,
(vii) Medium-large size with ejector—D07
(viii) Small-size die with movable stripper—D08
(ix) Small–medium die size with movable stripper—D09, and so on.
(x) Medium size with movable stripper—D10,
(xi) Medium-large size with movable stripper—D11,
(xii) Large size with movable stripper—D12,
(xiii) Extra-large size with movable stripper—D13,
(xiv) Medium-large size with ejector—D14.

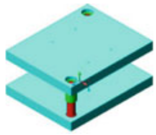
Each die size of the 14 die shapes has its own die components. Table 4 shows some of the 7 die sizes with the fixed stripper.

Table 4 Blanking die (fixed stripper)

Die-code (D01)				
				
Part	Die-block	Die holder	Punch	Punch holder
				
Die	Stripper	Thrust plate	Guides	Die-set
Die-code (D02)				
				
Part	Die-block	Die holder	Punch	Punch holder
				
Die	Stripper	Thrust plate	Guides	Die-set
Die-code (D03)				
		Nothing		
Part	Die-block	Die holder	Punch	Punch holder
				
Die	Stripper	Thrust plate	Guides	Die-set
Die-code (D04)				
				

(continued)

Table 4 (continued)

Part	Die-block	Die holder	Punch	Punch holder
				
Die	Stripper	Thrust plate	Guides	Die-set

3 Parametric Design in 2D

In the following sections, the parametric functions are discussed for 2D of fixed stripper medium-large size blanking die "D04" as it is the most popular die blanking size.

3.1 Blank Layout

Strip layout is generally done for the purpose of optimizing of the material utilization in blanking die design because averagely, the material cost takes 75 % of the entire cost of a stamped part. The resulting layout is determined by the nesting of two blanks to achieve the optimum material utilization.

Numerous studies have been carried out in blank nesting and a number of techniques have been developed and adopted, such as the Minkowski sum approach (Nye 1999), and the incremental rotation algorithm (Chow 1979; Nee 1984; Prasad et al. 1995; Lin and Hsu 1996).

In this system, we adopted the incremental rotation algorithm. When a blank, which can be a single one or a compound one consisting of more than one blank, is selected, the paired one is duplicated alongside of the initial one on its right side with a distance equal to the minimum bridge width between the blanks. At each rotation, the pitch is determined, the strip width is calculated with the minimum bridge width is added on both the top and the bottom of the blanks, and the material utilization is computed by

$$\eta = \frac{n \times A}{\mathrm{W} \times P} \times 100\,\%, \tag{1}$$

where η is the computed material utilization, n the number of blanks in the compound blank, W the strip width, and P the pitch of the layout.

A list of the data is generated for all the incremental rotational angles. The rotational angle corresponding to the maximum utilization may be adopted by the user or any other rotational angle may be chosen for engineering reasons. The material utilization data can be viewed graphically on in the dialog box, or in a data file, see Fig. 2.

It is logic to start blanking die design with the sheet metal nesting, as it is the process planning of the blanking die. Optimum and economical design of blanking die depends on the good laying of the blank on the strip. For this reason, taking blank layout into consideration for the design of blanking die is seen as a knowledge-based design parameter.

For the new economical layout position of the blank part, the system records this new position to be the start position for blank part in blanking die design process. Extreme coordinates of blank part are taken while the part lies in its new position.

For the blank (part) shown in Fig. 2, the optimum layout of the strip is shown in Fig. 3, which shows the material utilization report for the blank part in its proposed position. The system stores the blank part in its optimum position/orientation to control the punch position/orientation inside the die.

3.2 *Die Block Boundary*

The first parametric relation to be considered in the blanking die design is shown in Fig. 4. The blank part is surrounded by 4 points which represent the extreme points of the part. The points are the extreme upper point, the extreme right point, the

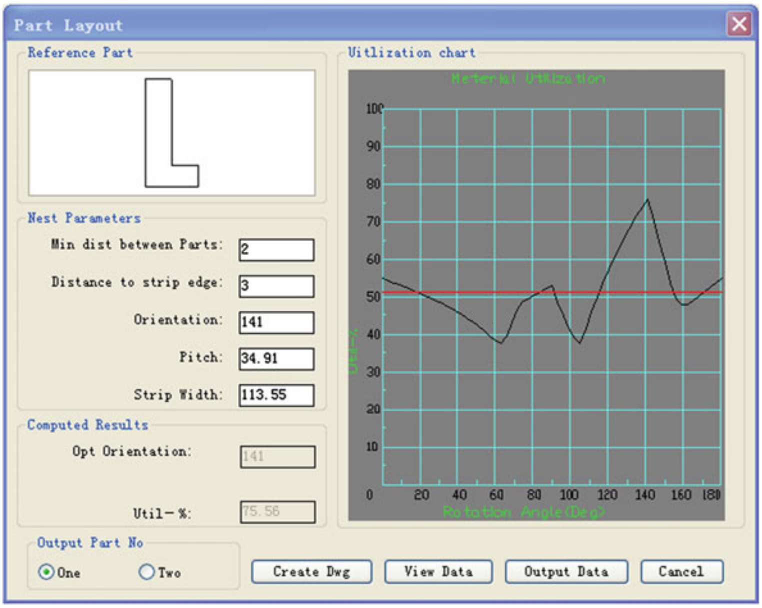


Fig. 2 Blank layout dialog box

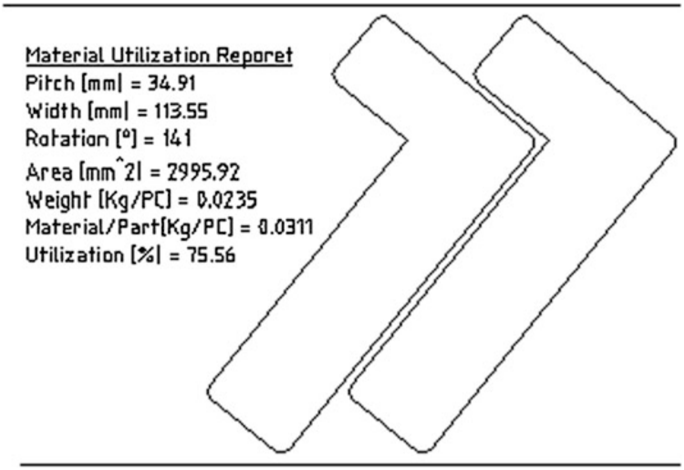


Fig. 3 Strip layout for the L-shaped blank

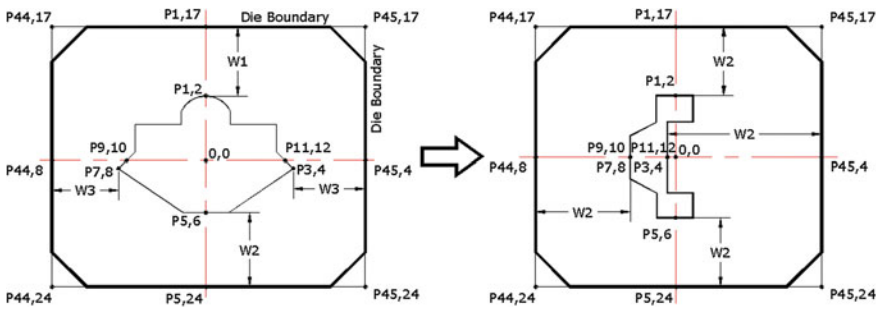


Fig. 4 Die block boundary

extreme lowest right point, and the extreme lowest left point. These extreme points may fall on three different elements, (points, lines, or arcs). If the point falls on any of these elements, then a specific equation must be applied. The determination of coordinates of extreme points for the blank part contour shape is important in case of margin estimation between blank part and boundary of die. Figure 4 shows an example of determination of extreme points for the blank part shape and the die block allowable margins.

To determine the parametric relationship of the fixed stripper medium-large size blanking die, we must note the following.

The first 12 points extracted from the blank part shape are used as the base for the other 114 parametric points which are required to accomplish the whole blanking die design. As the first 12 points are a function of the die block thickness "H" (Hussein 1999), therefore the cutting force which is determined from a formula as given below must be set first. So the die block thickness "H" which is function of cutting force can be determined.

$$P = \text{Cutting Force (Kp)} = 0.8 \cdot \sigma \cdot \text{ST} \cdot \text{CL} \cdot \text{FS}$$

where:

σ Material of Sheet Metal
FS Safety Factor
ST Strip Thickness
CL Contour Length (mm.)

$$\text{H} = \text{Die Block Thickness (mm)} = \sqrt[3]{P(\text{Kp})}$$

Wup = 1.2H(Case of Arc), 1.5H(Case of Line), 2H(Case of Point)
Wlp = 1.2H(Case of Arc), 1.5H(Case of Line), 2H(Case of Point)
Wmlp = 1.2H(Case of Arc), 1.5H(Case of Line), 2H(Case of Point)
Wmrp = 1.2H(Case of Arc), 1.5H(Case of Line), 2H(Case of Point)

It should be mentioned here that P1, P2 to P7, P8 as in Fig. 4 are the extreme points of the blank part, while P9, P10 to P11, P12 are the left and right intersection points of the blank part boundary with the horizontal axis passing through the center of pressure. The allowable margins are taken such that:

$$\text{W1} = 1.2\text{H for smooth curved edges of cut,}$$
$$\text{W2} = 1.5\text{H for straight edges of cut,}$$
$$\text{W3} = 2\text{H for pointed edges of cut,}$$

where, H is the die block thickness.

Figure 4 shows the fore-mentioned stated relationship between blank part shape and both of strip layout and die block dimension. The present methodology in this proposed die block design is dependent on P, which is the X coordinate of the upper point, will remain the same for the die block, and the P2, which is the Y coordinate of the upper point, will change to be P17 which equals to P2 + Wup. The most right point on the die block boundary P3, P4. P3 which is the X coordinate of the right point of the blank part, will be changed to P45 on the die block boundary, i.e., P45 = P3 + Wmrp. The P4 which is the Y coordinate of the blank part, will be the same on the die block. P5 which is the X coordinate on the lower point of the blank part will be the same on the die block boundary. P6 which is the Y-Coordinate of the lower point of the blank part, will changed to P24, which equals to P6—Wlp. P7 which is the X coordinate of the most left point on the blank part will be changed to P44, which equals to P7-Wmlp. Finally, P8 which is the Y coordinates of the blank part will be the same on the die block boundary.

3.3 Die Block Parametres

The whole die block boundary is determined as a function of the blank part extreme point coordinates or variables, and the die block margin as illustrated in the following formulas:

P17 = Y Coordinate of the Upper point − Die Block boundary = P2 + Wup
P24 = Y Coordinate of the Lower point − Die Block boundary = P6 − Wlp
P44 = X Coordinate of the max. Left point − Die Block boundary = P7 − Wmlp
P45 = X Coordinate of the max. Right point − Die Block boundary = P3 + Wmrp

By this method, the die block boundary could be determined as a merging point between the four outermost points. For example, the upper right corner is determined as a merging point between the (Y-Coordinate) upper point and the (X-Coordinate) most right point. The point is determined by taking the Y-coordinate from the upper point with the X-coordinate from the most right point.

The new created point is P45(X-Coordinate) and P17 (Y-Coordinate). Figure 5 shows the method of determining the die block boundary points.

3.4 Fasteners and Dowel Pin Position

Figure 6 illustrates some parametric relations (Akira 1982) to determine the fasteners position. This position is controlled between the die opening [a3 = 1d] and the outside edges of die block [a1 = 1.13d], and then the dowel pin position determined as [a2 = 1d] and measured from the fastener position. It must be noted that d is the fastener hole and value equal to [1.1d]. Moreover, Table 5 shows the recommended fasteners sizes for the designer to select as related to the die block thickness H (Akira 1982).

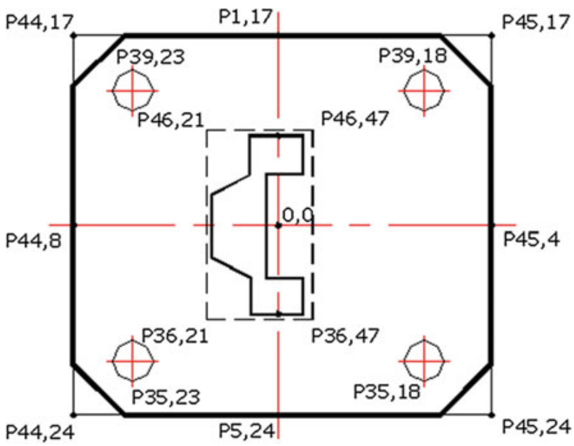


Fig. 5 Die block parameters in 2D

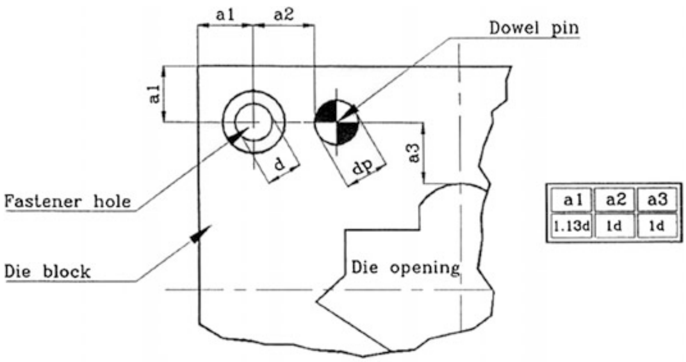


Fig. 6 The fastener and dowel pin position inside the die block (Akira 1982)

Table 5 Permissible screw size related to the die block thickness

Die thickness H (mm)	Screw size (mm)
≤13 mm	M4 to M5
13–19	M5 to M6
19–25	M6 to M8
25–32	M8 to M10
More than 32	M10 to M12

In Fig. 6, the parameters of the whole die block design in 2D are shown. The fastener position could be determined by adding new vertices P18, P23, P35, and P39. The vertices of the new parameters could be determined by applying the following parametric formulas:

$$P18 = P17 - 1.13 \times D$$
$$P23 = P24 + 1.13 \times D$$
$$P35 = P45 - 1.13 \times D$$
$$P39 = P44 + 1.13 \times D$$

Moreover, die opening can be determined by adding 1 mm to the blank part extreme points as follows:

$$P46 = P7 - 1$$
$$P47 = P2 + 1$$
$$P36 = P3 + 1$$
$$P21 = P6 - 1$$

3.5 Strip Boundary

The strip boundary is also a function of the sheet metal blank part extreme points and strip thickness. The resulted dimensions of the strip boundaries become the base of the guide rails boundary dimensions and spacing. Figure 7 shows the relationship between the part extreme points and the strip boundary.

To determine the strip layout boundary, the following parameters are considered.

Nup = the distance between the part upper point and the strip boundary
Nmlp = the distance between the part most left point and the strip boundary
Nlp = the distance between the blank most left point and strip boundary

Nup, Nmlp, and Nlp are taken as (1.5 X Strip Thickness), where -

Nup = the upper edge of the strip boundary
Nmlp = the most left point of the strip boundary
Nlp = The lower edge of the strip boundary

Then, the new point vertices are created to determine the boundary of the strip layout.

P20 = Y Coordinate of the Upper point—Strip Boundary = P2 + Nup
220 is taken as the value of the max right point of the strip boundary
P43 = X Coordinate of the Max Left point—Strip Boundary,
= P7—Nmlp
P22 = Y Coordinate of the Lower point—Strip Boundary,
= P6—Nlp

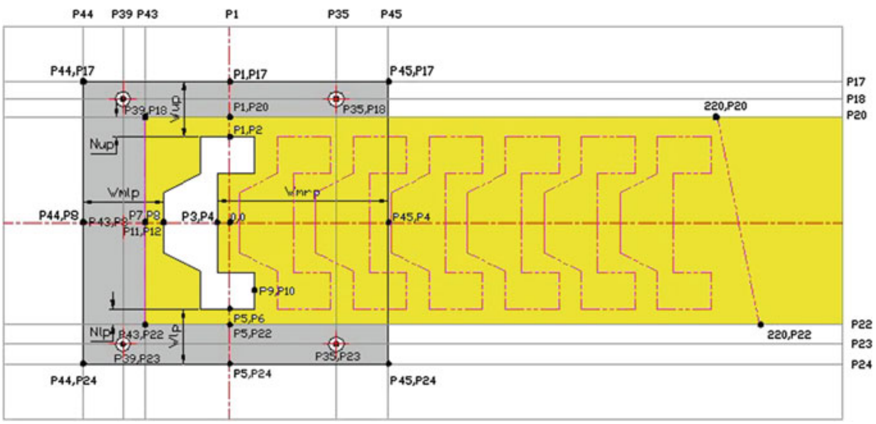


Fig. 7 Parametric relationships between blank part shape and both the strip layout and die block dimension

3.6 Parametric Relation of Die Holder Plate

In this section, the parametric relation of die holder plate is discussed as shown in Fig. 8. To get the die holder boundary, four more coordinates are added which are P27, P14, P32, and P42.

P42 = X Coordinate for the Upper-left corner-Die Holder Boundary = P44 − 24
P14 = Y Coordinate for the Upper-left corner-Die Holder Boundary = P17 + 24
P32 = X Coordinate for the Lower-Right corner-Die Holder Boundary = P45 + 24
P27 = Y Coordinate for the Lower-Right corner-Die Holder Boundary = P24 − 24

To get the Die Holder Opening, four more coordinates are added which are P46, P47, P36, and P21.

P46 = X Coordinate for the Upper-left corner-Die Holder Opening = P7 – 1
P47 = Y Coordinate for the Upper-left corner-Die Holder Opening = P2 + 1
P36 = X Coordinate for the Lower-Right corner-Die Holder Opening = P3 + 1
P21 = Y Coordinate for the Lower-Right corner-Die Holder Opening = P6 – 1

To get the fasteners and dowel pin positions for the die holder the following parameter formulas are considered:

P40 = X Coordinate of the Die-Holder left bolt position, = P42 + 1.13 × D
P38 = X Coordinate of the Die-Holder left pin position, = P40 + 1.3 × D
P37 = X Coordinate of the Die-Holder right pin position, = P34 − 1.3 × D
P34 = X Coordinate of the Die-Holder right bolt position, = P32 − 1.13 × D
P16 = Y Coordinate of the Die-Holder upper row fasteners = (P14 + P17)/2
P25 = Y Coordinate of the Die-Holder lower row fasteners = (P24 + P27)/2

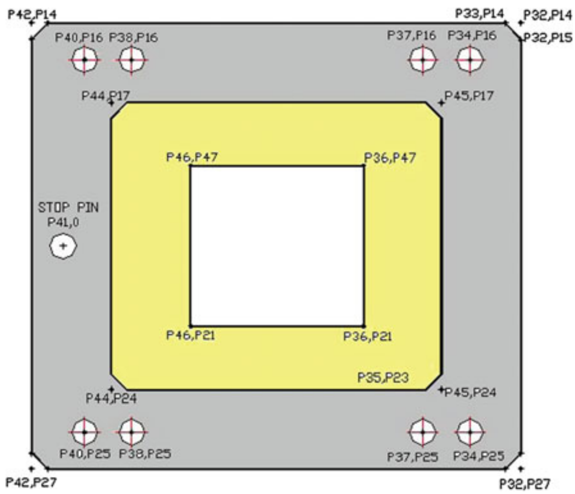


Fig. 8 2D die holder parameters

To get the position of the stop pin position, the following formula can be applied:

$$P41 = P44 - 12.5$$

3.7 Parametric Relation Between Die Holder Dimension and Die-Set Selection

The proposed system database includes seven different sizes of die-set which are used in an industry. To select the suitable die-set, the program checks the length and width of the die holder, and then checks which of company's die-set is suitable to include this die holder. Figure 9 shows the schematic drawing of die-sets. The main dimensions of die-set are presented in Fig. 10 in which the shadow area shows the available area to include the die holder. If the die holder dimensions exceeded the

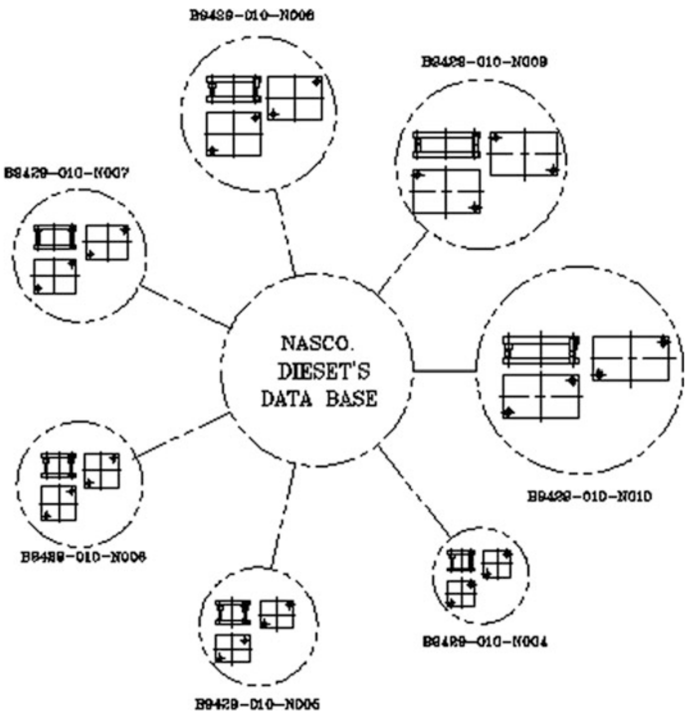


Fig. 9 The schematic drawing of die-sets

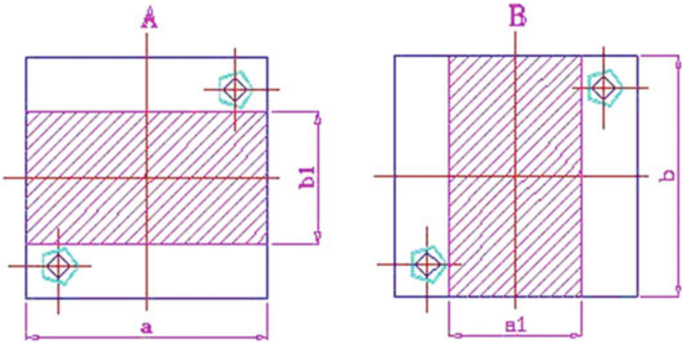


Fig. 10 The main dimensions of die-sets

shadow area, the program starts automatically and parametrically to design a new die-set (Hussein 2006). Moreover, Table 6 shows the decision table of die-sets for the products manufactured by the company provided with necessary dimensions.

To select the optimum die-set type and to define the position of the shank, a knowledge-based system is developed. The sample of rules incorporated in the proposed system is given in Table 7.

Table 6 Decision table of die-sets

Drawing No.	a × b	L	L1	Left (d1)	Right (d2)	a × b1	b × a1
B9429-010-N004	250 × 250	190	6	24/23/25	24/25/26	250 × 188	138 × 250
B9429-010-N005	315 × 250	200	8	22/31/33	30/29/31	315 × 119	184 × 250
B9429-010-N006	315 × 315	200	8	32/31/33	30/29/31	315 × 184	184 × 315
B9429-010-N007	400 × 315	200	8	32/31/33	30/29/31	400 × 184	269 × 315
B9429-010-N008	500 × 400	220	8	32/31/33	40/39/41	500 × 249	349 × 400
B9429-010-N009	630 × 400	220	8	42/41/43	40/39/41	630 × 249	479 × 400
B9429-010-N010	710 × 400	220	10	52/50/53	50/49/51	710 × 221	531 × 400

Table 7 Sample of rules incorporated in the knowledge-based system for selection of die-set type and shank position

IF	THEN
(P9 − P3) < 531& (P4 − P6) < 221	K = ((P4 − P6)/2) + 400, Insert B9429-010-N010
(P9 − P3) < 479& (P4 − P6) < 249	K = ((P4 − P6)/2) + 400, Insert B9429-010-N009
(P9 − P3) < 349& (P4 − P6) < 249	K = ((P4 − P6)/2) + 400, Insert B9429-010-N008
(P9 − P3) < 269& (P4 − P6) < 184	K = ((P4 − P6)/2) + 300, Insert B9429-010-N007
(P9 − P3) < 184& (P4 − P6) < 184	K = ((P4 − P6)/2) + 300, Insert B9429-010-N006
(P9 − P3) < 184& (P4 − P6) < 119	K = ((P4 − P6)/2) + 250, Insert B9429-010-N005
(P9 − P3) < 138& (P4 − P6) < 138	K = ((P4 − P6)/2) + 150, Insert B9429-010-N004

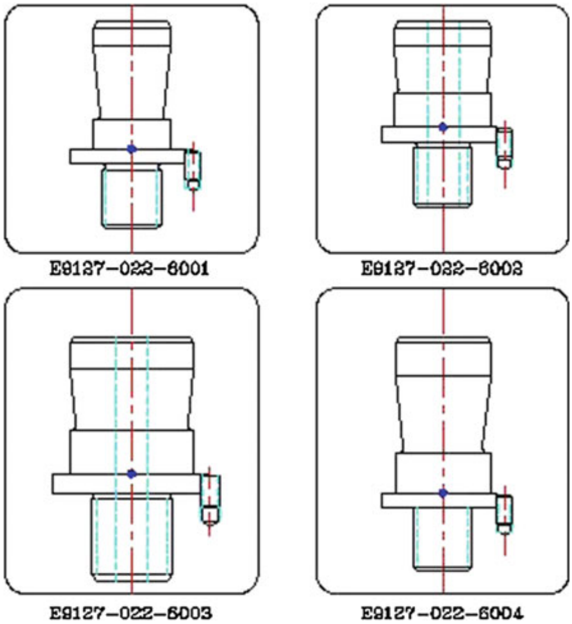
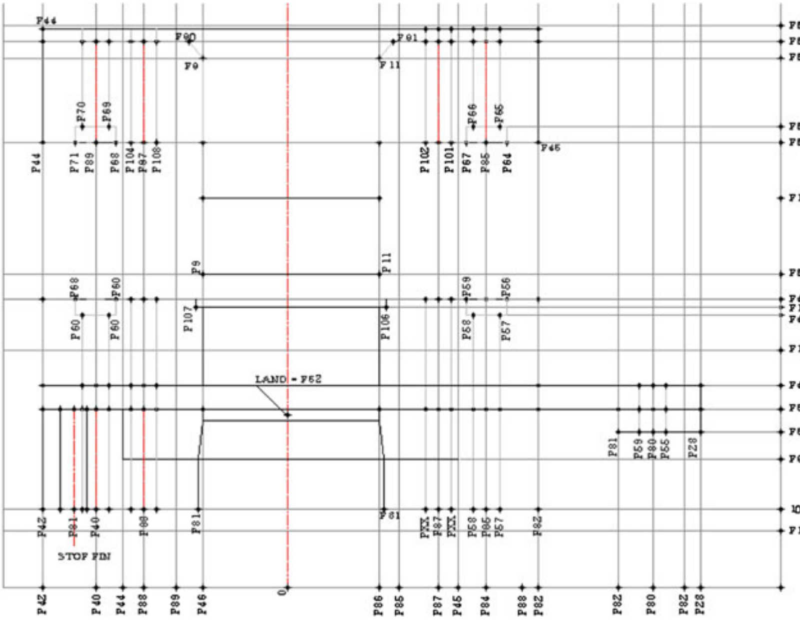


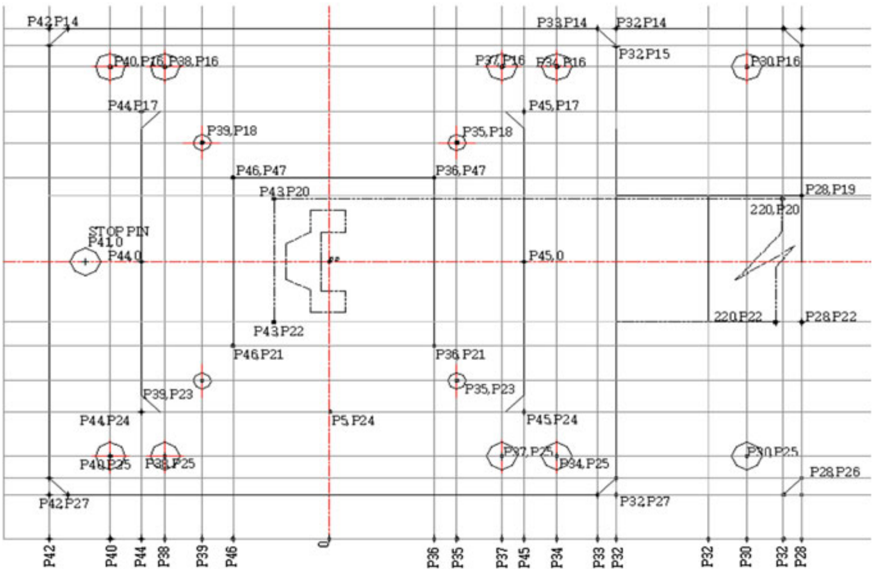
Fig. 11 Shanks database

If condition is within the required range, then the result will be as follows: The selected die-set drawing will insert automatically in its position in the AutoCAD drawing file with respect to the other items of the blanking die. The factor k will take a value. The value of k is responsible of the insertion point of the shank in the AutoCAD drawing file. The shank must be inserted in its position in the upper plate of the die-set. Databases of shanks are added for this reason to the system as shown in Fig. 11. Another *k* factors *k*1 and *k*2 are taken into consideration to decrease the number of parameters required for design and drafting of the blanking die.

The full sketch of the parametric blanking die design in 2D is illustrated in Fig. 12. It must be noted that the whole structure of the blanking die can be achieved by 114 variables. Those 114 variables are determined after a significant simplification of the drafting arrangement as illustrated in Fig. 12. The traditional drafting arrangement will cause a large number of variables which will be necessary for blanking die construction. The problem in 3D parametric designs is easier, since the computer deals with every component as package and the number of variables decreases significantly.

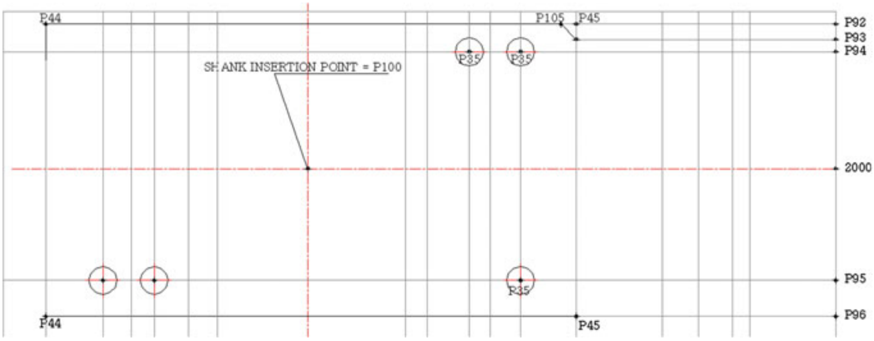


(a) Elevation of blanking die



(b) Plan for the lower group of blanking die

Fig. 12 Sketch of the parametric blanking die design in 2D



(c) Plan for the upper group of blanking die

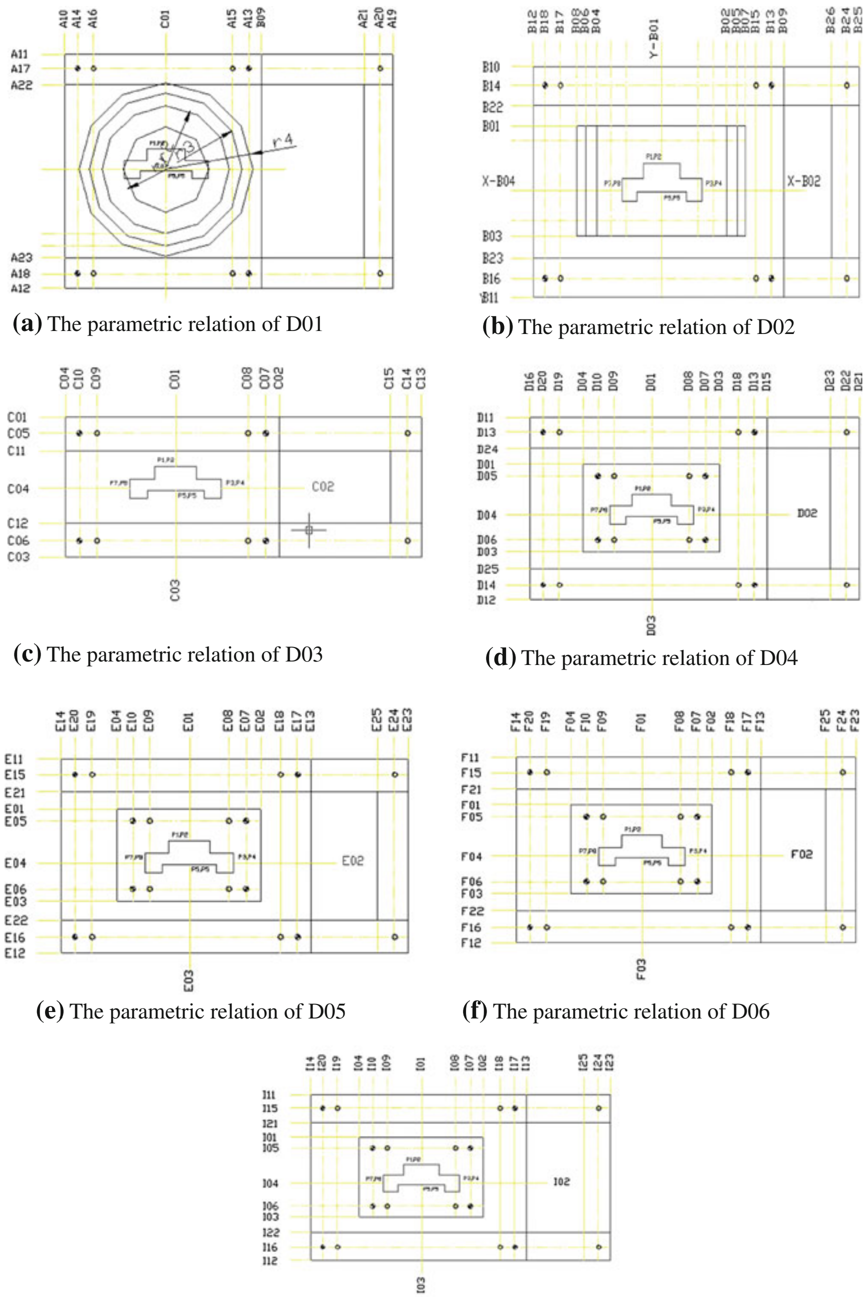
Fig. 12 (continued)

4 Parametric Design in 3D

The parametric design in 3D is slightly different from the previous one. Figure 13 is a schematic drawing shows seven different parametric relations, which describe the main design idea or the proposed die codes. Each of the proposed die code has its own features which are suitable for producing the optimum blanking die design. The results of the suggested parametric relations as described in Fig. 13 are illustrated in Table 4. The knowledge base concerned with this table is discussed in Hussein et al. (2008). The parametric relations translated into variables by using the visual basic program. It is very difficult to define all those variables for the different 14 subprogram into the visual basic.

As a progressive step, a nested parametric relationship is suggested as shown in Fig. 14. The nested technique decreases the number of variables from about 350 different variables to about 30 variables only. Table 8 shows the nested parametric formulas suggested for constructing all 14 die codes in 3D Blanking Die Design.

This progressive step–nesting in die code parametric relationships has led to another progress which is the nested program modules. Table 9 shows how the nested program module simplifies the suggested die code paths which are suggested in Table 4. Moreover, the nested modules include the sub nested modules. As example, the die opening is a separate module runs from inside the die block module. The die opening module is illustrated in Fig. 15. Moreover, Fig. 16 shows the assembly and the disassembly of a 3D blanking die design resulted from the system. A Case study for selecting of AutoCAD version, selection of the optimum die code, and finally constructing 3D die design are shown in Figs. 17, 18, and 19 respectively



(a) The parametric relation of D01

(b) The parametric relation of D02

(c) The parametric relation of D03

(d) The parametric relation of D04

(e) The parametric relation of D05

(f) The parametric relation of D06

(g) The parametric relation of D07

Fig. 13 The parametric relation of the die code for 3D blanking die design

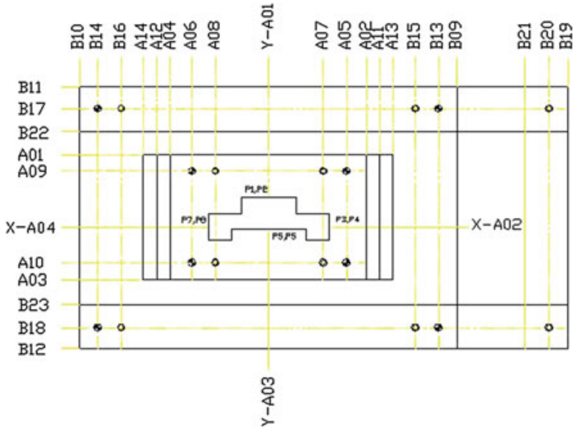


Fig. 14 The nested parametric relation for the 3D blanking die design

Table 8 Nested program modules in case of blanking die

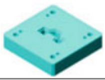
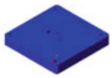
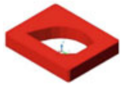
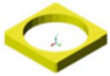
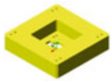
Die code	D01	D08	D02	D09	D03	D10	D04	D11	D05	D12	D06	D13	D07	D14
Die block														
Die holder					Nothing									
Punch														
Punch holder														
Stripper	 Fixed stripper				+					 Movable stripper				
Thrust plate														
Guide plates														
Die set	As discussed in Sect. 2.6 in Chap. Generic classification and representation of shape features in sheet-metal parts.													
Ejector	Nothing													

Table 9 3D nested parametric relationships in case of blanking die

Die part	Parametric design formula	3D Part shape
Die block	In case die code D01 and D07 R1 = Determined by program code R2 = R1 + 5, R3 = R1 + 10, R4 = R1 + 11, R5 = R1 + 1	
	In case die code D02 and D09 A01 = P2 + Wup, A02 = P3 + Wmrp, A03 = P6 − Wlp, A04 = P7 − Wmlp	
	Die code D03, D04, D05, D06, D07, D010, D11, D12, D13, D14 B09 = A02 + 24, B10 = A04 − 24, B11 = A01 + 24, B12 = A03 − 24 B13 = B09 − (5 + d/2), B14 = B10 + (5 + d/2) B15 = B09 − (10 + d + (1.8 * d/2)), B16 = B10 + (10 + d + (1.8 * d/2)) B17 = B11 − (5 + d/2), B18 = B12 + (5 + d/2)	
Die holder plate	In case die code D01 and D07 B09 = R2 + 10, B10 = −R2 − 10, B11 = R2 + 10, B12 = −R2 − 10	
Stripper plate	In case die code D02 and D09 A11 = A02 + 5, A12 = A04 − 5, A13 = A11 + 1, A14 = A12 − 1	
Thrust plate	Die Code D04,D05,D06,D07,D11,D12,D13,D14 A05 = A02 − (5 + d/2), A06 = A04 + (5 + d/2), A07 = A02 − (10 + d + (1.8 * d/2)), A08 = A04 + (10 + d + (1.8 * d/2)) A09 = A01 − (5 + d/2), A10 = A03 + (5 + d/2)	
Guide plates	B19 = B09 + 100, B20 = B19 − (5 + d/2) B21 = B20 − (5 + d/2), B22 = B11 − (10 + 1.8 * d) B23 = B12 + (10 + 1.8 * d)	

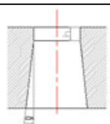
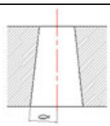
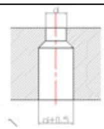
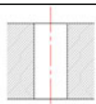
			
Apply on	Apply on	Apply on	Apply on
D02,D03, D04,D05, D09,D10, D11,D12	High accuracy Compound die	D06,D07 D13,D14	D01, D08 And Piercing

Fig. 15 Straight land and relief angle

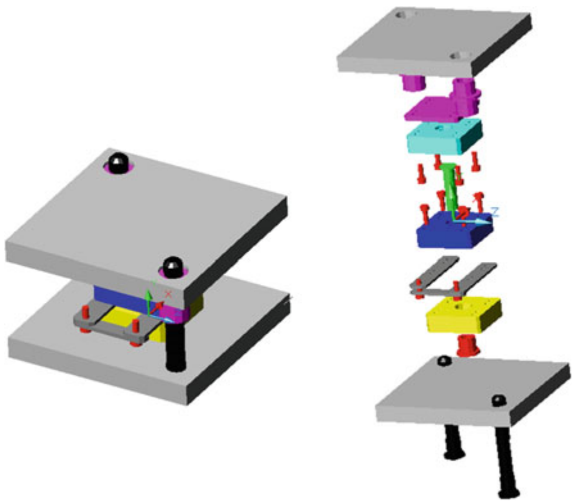


Fig. 16 The assembly and disassembly of the fixed stripper small size blanking die example

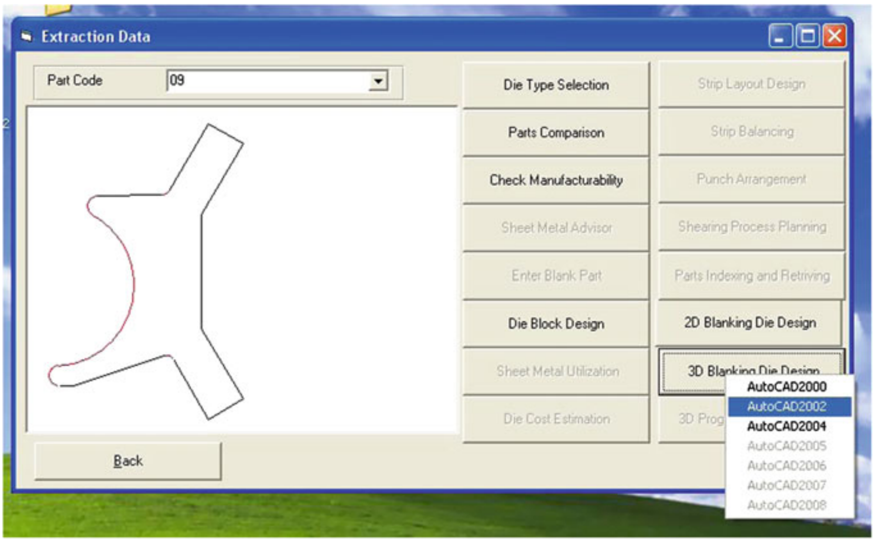


Fig. 17 Selection of the AutoCAD version

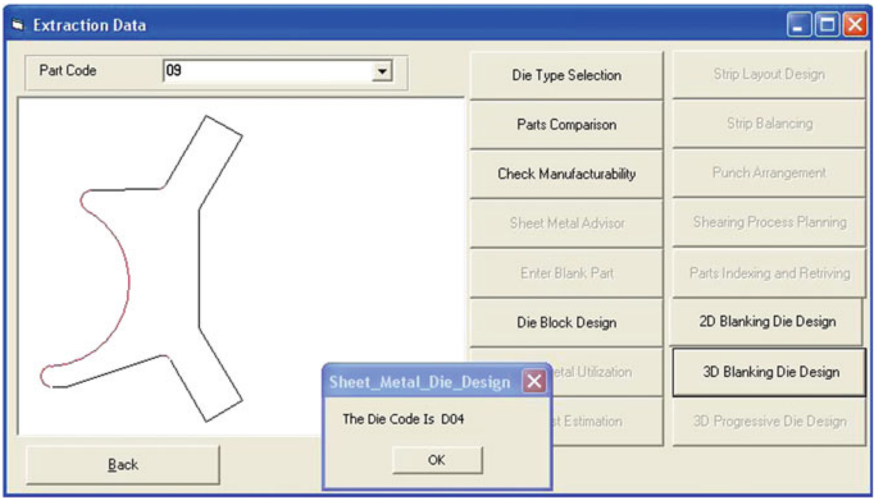


Fig. 18 Automatic recognize of die code

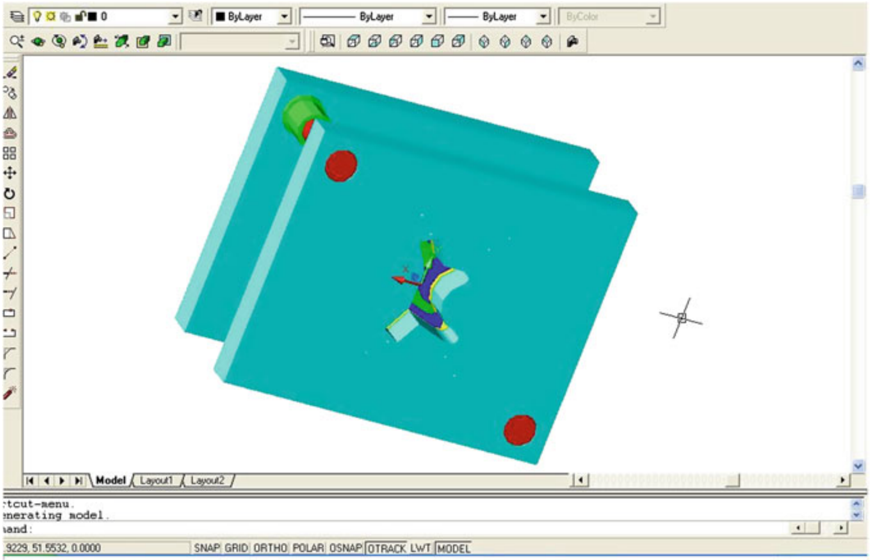


Fig. 19 The automated design of 3D blanking die

5 Conclusion

Parametric design of the sheet metal blanking die in both 2D and 3D is discussed. The parametric formulas for each component in both 2D and 3D are described in details. A list of 14 different shapes of the blanking die is also described, in both of fixed stripper type and movable stripper type. An innovation of nesting the 14 shapes into similar modules is also shown in this chapter. The proposed system can be foundation for development of a knowledge-based system for automated design of all types of sheet metal dies.

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Knowledge-Based System for Design of Deep Drawing Die for Axisymmetric Parts

Vishal Naranje and Shailendra Kumar

1 Introduction

Deep drawing operation is one of the widely used sheet metal forming processes due to ease of forming complex shapes, high strength to weight ratio, short production time, etc. It is popular because of its rapid press cycle to produce complex axisymmetric geometries (Kalpakjian and Schmid 2009). Deep drawn parts are used in subassemblies of automobile, food processing, beverage, pharmaceuticals, computers, medical, refrigerators, kitchen utensils, electrical, micro-electronics, and telecommunication equipments. In context with production of axisymmetric deep drawn parts using mechanical presses, variety of processing methods like single action die, double action die, combination dies, transfer die, etc., are being used. Figure 1 shows a schematic of deep drawing process for producing an axisymmetric part.

One of the important tasks in the production of deep drawn sheet metal parts is the design of deep drawing dies to suit the product features. One of the important aspects for successful production of defect free production of deep drawn parts depends on quality of die design. The process of design of deep drawing die involves a number of activities such as calculation of blank size, process planning, design/selection of die components, and modeling of die components and die assembly. Traditionally these tasks are carried out manually by highly experienced die designers and process planners. Various problems in traditional die design process are (i) scarcity of experienced die designers worldwide, (ii) it is complex, time consuming, trial and error process, (iii) quality of sheet metal parts are not

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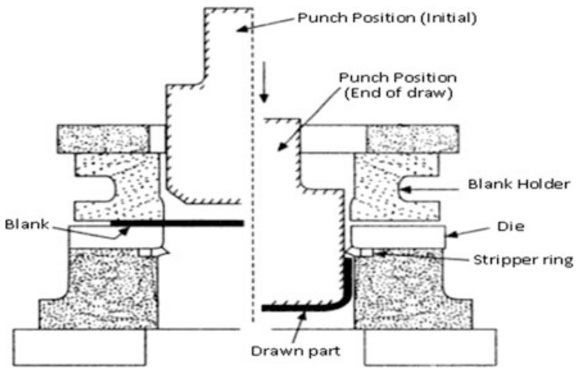


Fig. 1 Deep drawing process (Kaushish 2010)

consistent, and (iv) frequent mobility of experienced die designers and process planers.

Since early 1970s, a number of commercial softwares have been developed to assist die designers to perform the task of die design. These CAD/CAM softwares provide some aid to die designers and process planners to perform simple calculation, storage and retrieval of data, visualization of part geometry and drafting of die. These packages have shown their capability through increase in productivity of die designers to some extent. Nowadays, there are number of commercial CAD/CAM systems available for sheet metal industries. But most of these CAD/CAM systems provide the solution for specific die design tasks for very simple sheet metal parts. Also multiple software packages are required to perform various activities of die design process and small scale industries (especially in developing countries) are not able to afford these commercial softwares because of their high installation cost. Further trained competent persons are required to operate and interpret the results of these commercial software packages.

Therefore, there is a need of development of a KBS for automatic design of deep drawing dies. The system must be capable to automate all major activities of traditional die design process including process planning, strip-layout design, selection of die components and die modeling. In this chapter, a KBS developed for automatic design of deep drawing die for axisymmetric parts is described. The production rule-based approach of AI is utilized for development of this system. Capability of the developed system is tested on various types of industrial deep drawn parts.

The next section describes the literature review in the domains of computer-aided process planning (CAPP), computer-aided die design, and KBS for deep drawing die design.

2 Literature Review

2.1 Computer-Aided Process Planning

Several researchers applied efforts in developing computer-aided process planning (CAPP) systems for deep drawn parts using various AI techniques. For example, Karima and Richardson (1987) pioneered the idea of applying KBS in sheet metal forming. The system consists of manipulating the knowledge as facts, procedures, judgment, and controls which can be acquired from relevant sources. This system advices the user what action to be taken to achieve the desired goal keeping in perspective various design constraints. Later on Karima (1989) presented a hybrid system for process planning in sheet metal forming. System takes the overview of stamping engineering from micro and macro perspectives. The role of computer modeling is also examined with emphasis on applicability of different computer tools and need for a broad methodology to support application of computer tools. Sitaraman et al. (1991) developed a hybrid computer-aided engineering (CAE) system for automatic process sequence design for manufacturing of axisymmetric deep drawn parts. They integrated expert system module and a process modeling analysis module for handling symbolic and numeric information. Tisza (1995) from University of Miskolc, Hungary developed a Metal Forming Expert (METEX) system for sheet metal forming applications. The system used AutoCAD and AutoLISP to generate possible solutions for deeply formed shapes. An expert system namely ASFEX (Axisymmetric Sequence Forming Expert System) was developed by the Engineering Research Centre for Net Shape Manufacturing (ERC/NSM) (Esche et al. 1996). This system used design rules to generate process sequences for multistage drawing of round cups and tool geometry for each station of the sequence. In process sequence design, both geometry and formability based decisions are taken. The process is then analyzed by finite element simulation to check the feasibility of the production. Sing and Rao (1997) constructed a knowledge-based CAPP system using decision tables for axisymmetrical deep drawn cup. Researchers from Center for Net Shape and Die Manufacturing, Pusan University, South Korea (Park et al. 1998) developed a rule-based CAPP design system namely Pro_Deep for generation of process sequence with intermediate object geometry and also to determine process parameters. Knowledge is represented in 'IF-THEN' type of production rules. Similarly a compact and practical CAD/CAM system for the blanking or piercing of irregular shaped sheet metal products was developed by Choi et al. (2000). The program for the system was written in AutoLISP language for strip and die layout of stator and rotor parts with bending and piercing operations. Choi et al. (2002) used case-based reasoning (CBR) approach to develop a modular design support system for production of circular cup. System suggests various possible process sequences for circular cup. Kang and Park (2002) constructed a rule-based expert system for process planning of multistage non-axisymmetric deep drawn parts having elliptical cross-sectional shape. System includes 3-D modeling, blank size calculation, and process planning module. Shi et al. (2002) proposed prototype knowledge-based process planning system for auto panel. The system consists of process planning and forming analysis modules. Case-based and rule-based reasoning approach is used and supported with the CAD tool Unigraphics (UG)-II. Park and Prasad (2004, 2005) developed a surface area calculating system (SACS) and CAPP system for non-axisymmetric deep drawn parts with elliptical shape. Researchers Wifi et al. (2004, 2005) from Cairo University, Egypt reported to develop a CAPP system using rule-based technique for complex axisymmetric circular and rectangular deep drawn parts. This system is coded using Visual Basic (VB) and interfaced with AutoCAD software. George-Christophe et al. (2005) used logic programming for process planning of sheet metal forming with progressive dies. Zhang et al. (2006) developed a CAPP system for multistage, non-axisymmetric deep drawn parts using CBR approach. It is implemented in a C language integrated production system (CLIPS) and interfaced with the Solid Edge CAD system. Abbassi and Zghal (2007) proposed a CAPP system based on the experimental results and empirical knowledge of experts for axisymmetric deep drawn parts. Outputs of the system are in the form of stamping process parameters and geometrical modeling of tool. Potocnik et al. (2011) developed an intelligent system for automatic calculation of stamping process parameters for design of stamping die for manufacturing of circular cup with flange. Further they also reported to develop a KBS for modeling of the reinforcement of a press plate (Potocnik et al. 2012). This system is based on the implemented knowledge of experts in the execution of design, material selection, and numerical analysis based on FEM. Fazli et al. (2014) developed a computer-aided design (CAD) system for automatic process design and finite element (FE) modeling of axisymmetric deep drawn components using the theoretical and experimental rules.

2.2 Computer-Aided Die Design

From early 1970s to mid-1980s, the first generation CAD systems for die design were developed to reduce time, cost and to minimize trial and error adjustments in die design process. Schaffer (1971) was probably the pioneers in use of computer in die design. The system namely PDDC (Progressive Die Design by Computer) was developed to identify projections of the part which may subject the die to undue stresses during cutting operation. Later on (Fogg and Jaimeson 1975) proposed an improved PDDC system by considering other factors which influence the die design. The system has different modules to perform various tasks for die designer such as strip-layout, die layout, etc. But it takes long design time due to its semi-automatic nature. Later on number of researcher including Nakahara (1978), Adachi et al. (1983), Shirai and Murakami (1985), Altan (1987), Bergstrom et al. (1988), Prasad and Somasundaram (1992), Nee (1994), Choudhary and Allada (1999) developed CAD/CAM system for automation of progressive die design.

Very few researchers applied their efforts to develop CAD system to automate design of deep drawing die. For example, Park (1999) proposed a prototype CAD/CAM system for axisymmetric deep drawing processes in simple action press. The system was written in User Programming Language (UPL) and developed under the environment of Personal Designer CAD/CAM software. The system needs expert designer's assistance for analysis of final results. A fully integrated CAD/CAM/CAE system was developed by Lin and Kuo (2008) for stamping dies of automotive sheet metal parts. The system operates using high end softwares like CATIA for layout diagram design and die structure analysis, STRIM software for die face design, DYNAFORM for formability analysis and CADCEUS for tooling path generation and simulation. Lin and Kuo (2011) presented a method to explore multi-objective optimization in the structural design of ribs for drawing dies by combining Finite Element Analysis (FEA) and the fuzzy based taguchi method.

The foregoing literature review reveals that only few research efforts are found in the area of CAD of deep drawing die. Most of the reported systems are semi-automatic, dedicated to specific type of application, and need experienced die designers to operate the system.

2.3 Knowledge-Based Deep Drawing Die Design

Eshel et al. (1986) developed a rule-based expert system for generation of process plan for axisymmetric and monotone parts produced by deep drawing process. They suggested G & TR (Generate & Test and Rectify) strategy for the process planning of axisymmetric deep drawing products. Xiao et al. (1990) proposed an expert system using a set of production rules and frames for designing process sequence of strip-layout design of progressive drawing of simple axisymmetric parts. Tisza (1995) from University of Miskolc, Hungary developed a Metal Forming Expert (METEX) system for sheet metal forming applications. The system used AutoCAD and AutoLISP to generate possible solutions for deeply formed shapes. An expert system namely ASFEX (Axisymmetric Sequence Forming Expert System) was developed by the Engineering Research Centre for Net Shape Manufacturing (ERC/NSM) (Esche et al. 1996). This system used design rules to generate process sequences for multistage drawing of round cups and tool geometry for each station of the sequence. A compact and practical CAD/CAM system for design of die for irregular shaped stator and rotor parts with bending and piercing operations was developed by Choi et al. (2000). Researchers at Indian Institute of Technology, Bombay, Mumbai, India (Pilani et al. 2000) proposed a neural network and knowledge-based approach to design a hybrid intelligent system for generating an optimal die face for forming dies. Researchers from Department of Mechanical and Automation Engineering, National Kaohsiung First University of Science and Technology, China (Lin and Hsu 2008a; Lin et al. 2008a, c) developed a knowledge-based parametric design system to automate the design of main components of drawing die (Lin 2008a). Similarly they also developed another automated die design system using prebuilt design knowledge-base and database on the platform of CATIA software (Lin 2008b). Further, researchers also developed an integrated CAD/CAM/CAE system for design of an automobile stamping die using concurrent engineering approach (Lin 2008c). Some researchers (Lin et al. 1989; Cheok et al. 1994; Huang et al. 1996; Ismail et al. 1995, 1996; Singh and Sekhon 1996, 1998; Kim et al. 2002; Chu et al. 2004, 2008; Tor et al. 2005; George-Christophe et al. 2005; Kumar and Singh 2007a, b, c, 2008, 2011; Hussein et al. 2008; Giannakakis and George-Christopher 2008; Ghatrehnaby and Arezoo 2009; Tsai et al. 2010) developed KBSs for design of single operation dies (shearing, blanking, bending, etc.) and progressive dies.

The reviewed literature on CAPP, computer-aided die design, and knowledge-based deep drawing die design systems reveals the growing interests of worldwide researchers and technocrats in the area of automation of sheet metal die design process using various CAD systems and AI techniques. Limited research efforts are found in the area of automation of deep drawing die design. Even these reported systems are not capable to automate all activities of traditional die design process. Further these systems need considerable interactive inputs from experienced die designers and finally to take appropriate decisions at various stages of die design process planning, strip-layout design, selection of type and size of die components; and die modeling.

3 Considerations for Design of Deep Drawing Die

3.1 Process Planning

During process planning of deep drawing, the die designer or process planner has to determine various process parameters such as limiting draw ratio, die radius, punch radius, clearance between punch and die, punch velocity, type of lubricant etc. (Naranje and Kumar 2013a). These process parameters depend on sheet material, sheet thickness, type of die, accuracy requirement and complexity of part geometry, etc. Generally the limiting draw ratio (blank diameter to cup diameter) is taken as 1.8 for aluminum; 1.9 for steel and 2.0 for stainless steel sheet material. Die radius should be four to six times of material thickness for steel and five to ten times for stainless steel and aluminum. Punch radius should be at least four to eight times of material thickness for steel, and eight to ten times for aluminum sheet material. Generally it is recommended that punch-die clearance should be at least 1.10 times of sheet thickness. Experienced process planners recommend that punch velocity should be 0.4 m/s for deep drawing of steel and 0.15–0.2 m/s for stainless steel and aluminum alloys. Lubricants must be checked for compatibility with sheet material.

3.2 Strip-Layout Design

For the design of strip-layout, die designer has to identify the operations required and their sequence; and determine the details of each operation for production of defect free deep drawn parts (Naranje and Kumar 2013b). Design features of different part types should be produced at separate stations. If there is a hole inside the deep drawing shape, then it should be worked after the deep drawing operation. When two stages are used to lance the strip, there should be minimum 3.0 mm distance between two lance operations. Sequence of operations should be in such a way that all features and tolerances can be controlled. Once the sequence of operations is established, idle stations can be inserted if necessary. Idle stations are included to strengthen a die and to incorporate future design modifications. The strip width and feed distance depend on the sheet thickness, dimensions of blank, direction of sharp edge of sheet, and number of stations. Where deep tapered shells are required with a height to diameter ratio of greater than one half, a stepped shell with vertical walls should be first produced and then redrawn to produce the final shape.

3.3 Selection of Die Components

Selection of type and size of die components is a vital step in the design process of a deep drawing die. A deep drawing die consists of several components including die block, die gages, strippers, stripper plate, punch plate, back plate, die-set, and fasteners. The size of die block depends on sheet thickness, sheet material, direction of sharp edge of strip, strip size, and die material. Dimensions of die gages mainly depend on size of stock strip. It is necessary to maintain a minimum gap of about 5–10 times of sheet thickness between fixed stripper plates and die plate. The size of stripper plate corresponds to the size of die block. Stationary strippers are provided with a milled channel in its bottom surface to accommodate and guide the strip material. The width of channel in the stripper should be equal to the strip width plus adequate clearance to allow for variations in strip width. The height of the channel should be at least equal to 1.5 times of sheet thickness. The stripping force depends on several factors such as type and thickness of strip, lubrication, any galling or metal pickup on the punch, and sharpness of punch and die. The thickness of punch plate depends on punch diameter. Length and width of punch plate are usually same as that of die block. Backup plates are hardened and normally interposed between small perforator punches and punch holder. The backup plate is generally about 10–12 mm thick.

A die-set is a unit component constituted of punch holder, die holder, guide post, and guide bush. Open die-set is generally used to manufacture simple parts in small quantities and where loose tolerances are required. Pillar die-set is used where greater accuracy is required. Dimensions of die-set depend on part quantity, dimensional tolerance of the component, clearance between punch and die, and clearance between guide posts and bushings. Type of die-set is selected by considering size of the press opening, requirements for strength and stability of the tool, amount of downtime and cost to regrinding, ease in maintenance and repairs and for assembly as well. Die shoe forms the base of the die-set and in majority of die-sets the guide posts are mounted on it. The die shoe thickness is based on how much force can be expected during cutting and forming operations. The length of guide-posts should be sufficient so that it never come out of their bushings during the press operation (Smith 1990). The guide pins should be 6.5 mm shorter than the shut height of the die. For selection of die-set, die designer needs to determine the type and size of die-set (Waller 1978). Selection of the type of die-set depends on the type of sheet metal operation, part quantity, and job accuracy. Dimensions of the die-set depend upon the length and width of the die and its placement in the die-set. The primary purpose of fasteners is to clamp together all the die components in a safe and secure manner. Whenever possible hex-socket head cap type screws should be used. For die-sets of greater weight, an additional socket cap screw should be inserted through the upper die shoe to the underside of the ram. Screw head holes must be counter-bored in the die section and screw threads must enter into die components at least 1.5 times of its diameter. To achieve the precise alignment at least two dowels per block are essential and must be press-fitted. The number and size of screws are determined by estimating the space available and the load to be resisted. Generally four Allen bolts are used at the four corners of die block.

3.4 Modeling of Die Components and Die Assembly

Modeling of plate elements of a die requires the dimensional data of die block, die gages, stripper plate, punch plate and back plate. For automatic 2-dimensional (2-D) modeling of plate elements of deep drawing die, drawing commands of AutoCAD such as LINE, PLINE, CIRCLE, FILLET, LAYER, etc., can be invoked. Similarly, for 3-dimensional (3-D) modeling of die components and die assembly in the drawing editor of AutoCAD software, AutoCAD commands such as ORBIT, EXTRUDE, UNION, SUBTRACT, REVOLVES, SWEEPS, etc., can be invoked (Naranje and Kumar 2013c).

Based on the above considerations, a KBS, namely, INTDDD (*Int*elligent *D*esign of *D*eep *D*rawing *D*ies) is developed for intelligent design of deep drawing dies.

4 Intelligent Design System: INTDDD

4.1 Methodology for Development of Proposed System

Various steps involved in development of proposed system are knowledge acquisition, framing of production rules, verifications of production rules, selection of

Table 1 A sample of production rules included in the system INTDDD

S. No.	IF(condition)	THEN (action)
1	Ratio of flange diameter to cup diameter < 1.1; and 0.0006 ≤ Ratio of sheet thickness to blank diameter < 0.002	Set the ratio of cup height to cup diameter ≤ 0.50
2	Sheet material = Extra deep drawing steel; and 0.0008 ≤ Ratio of sheet thickness to blank diameter < 0.0015; and Draw stage = Fourth	Set limiting draw rate ≤ 0.86
3	Sheet material = M.S. EDD; and Ratio of flange diameter to cup diameter ≤ 1.1	0.0006 ≤ Set the thickness ratio > 0.02
4	Material = Mild steel; and Draw = First	Set clearance = 1.40 times of sheet material thickness
5	Material = Mild Steel; and Type of press = Single action	Set the drawing speed = 0.30 m/s
6	Sheet material = M.S. EDD; and Sheet material thickness (mm) ≤ 1.0	Set the blank holder pressure = 0.20–0.25 N/mm^2
7	Draw Stage = First; and Diameter of first stage (d_i) ≤ Shell diameter (d)	Drawing force in first stage (N), $F_i = \pi d_i t \sigma_y \left(\frac{D_b}{d_i} - 0.7\right)$
8	100 mm < Punch diameter < 200 mm	7.0 < Air vent hole diameter (mm) < 8.0
9	Sheet Material is mild steel; and Sheet thickness < 0.5 mm	Lubricant = Mineral oil; SP—Emulsion; grease
10	Four times of sheet thickness ≤ die radius > 10 times of sheet thickness	Accept die radius
11	Drawn Part = Taper; and Primitive shape under deformation = taper; and Section = upper; and Percentage reduction in first stage (PRui) ≤ 50 %	Percentage Reduction, PRui = $100\left(1 - \frac{d_u}{D_b}\right)$
12	Required operations on part: Deep drawing, Lancing, Piercing, Blanking, Parting	Preferred sequence of operation: First—Lancing, Second—Deep drawing, Third—Piercing, Fourth—Blanking, and Fifth—Parting
13	−0.1 < Tolerance on part (mm) < +0.1; and Cut an interior section without removing the section from sheet	Required operation = Lancing
14	−0.1 < Tolerance on part (mm) < +0.1; and Produce deep recess on part	Required operation = Deep drawing
15	No hole exists on the part, and	Locate pilots on the scrap sections formed by the notching operation

(continued)

Table 1 (continued)

S. No.	IF(condition)	THEN (action)
	no notching operation (on opposite sides) to be done on the part	
16	Required operations on part = Notching (one), deep drawing (4 Stages), Parting, Blanking, Trimming; and There is possibility of future engineering changes in the par	No. of stations = 10 Preferred staging: First station: = Pilot piercing Second station: = Notching Third station: = First draw Fourth station: = Second draw Fifth station: = Idle Sixth station: = Third draw Seventh station = Fourth draw Eighth station = Trimming Ninth station: = Blanking Tenth station: = Parting off
17	Sheet thickness (mm) < 3.0; and Blank diameter (mm) ≤ 10.0	Select sheet length (mm) = (Blank diameter + 2.8) × Number of stations
18	Sheet thickness (mm) ≤ 0.80; and 25 < Blank diameter (mm) ≤ 75.0	Select sheet width (mm) = Blank diameter + 3.0
19	30 ≤ Blank diameter (mm) < 60; and 3.0 ≤ Sheet thickness (mm) < 6.0	Feeding space = 2.5 mm, Carrier width = 3.5 mm, and Bridge width = 4.0 mm
20	4.0 < Sheet thickness (mm) ≤ 6.0; and Die material = Tool steel	Select die block thickness = 32 mm
21	Cup diameter (mm) < 22; and 1.0 < Sheet thickness (mm) ≤ 2.0; and Die material = Tool steel	Select width of die block = (Sheet width + 24 mm)
22	50 ≤ Cup diameter (mm) < 80; and 1.5 < Sheet thickness (mm) ≤ 2.0; and Die material = Tool steel	Select length of die block (mm) = (Strip length in mm +40)
23	1.0 ≤ Sheet thickness (mm) < 3.0; and Type of feed = automatic	Select the minimum thickness of die gage = 8.0 mm; and Distance between die gages (mm) = (Strip width + 1.5)
24	60 < Cup diameter (mm) ≤ 70; and 1.5 < Sheet thickness (mm) ≤ 3.0	Set negative tolerance on punch = 0.04 mm, Select circular punch of length = (cup height + 42 mm), Punch plate thickness = 18 mm, and Back plate thickness = 6.0 mm
25	Operation = Deep drawing; and Batch production quantity ≥ 10,000; and 0.025 ≤ precision on part (mm) ≤ 0.1; and Clearance (mm) ≤ 0.0225	Select die-set with four ball bearing bushings on top bolster and four guide pillars on lower bolster
26	350 < Working area (mm2) ≤ 700 (parallel to die-set); and Tolerance required on part (mm) ≤ 0.01	Place die in the 4 pillar die-set with pillar diameter 35 mm bush diameter 50 mm and bolster dimensions in mm as-length = 905, width = 400, and height = 60

knowledge representing language, identification of hardware, development of knowledge base, and construction of user interface (Kumar and Singh 2004; Kumar et al. 2006). Domain knowledge for development of the proposed system is essentially collected by online and off line discussion with experience die designers, process planners, design consultants, and shop floor engineers of different stamping industries, and reviewing published research articles, industry catalogs and manuals. Heuristics knowledge acquired for each module of the proposed system was framed into the production rules of IF (condition)-THEN (action) variety. These production rules framed for each module were cross-checked from other teams of die design experts by presenting them IF-condition of the production rule of IF-THEN variety. The system overall comprises of more than 1000 production rules of IF-THEN variety. A sample of production rules so framed, verified and thereafter incorporated in various modules of the proposed systems is given in Table 1 (Naranje and Kumar 2012, 2013a, b, 2014a, b). The sequencing of production rules is unstructured as this arrangement allows insertion of new production rules even by a relatively less-experienced knowledge engineer. Knowledge base of the proposed system is constructed by coding of production rules using AutoLISP language. The user inputs' information provides guidance to the inference engine as to what 'IF-THEN' rules to fire and which process of information are needed from the knowledge base. In the proposed system forward chaining search strategy is used for searching the solution. User interface of the system is developed using Visual Basic 6 and interfaced with AutoCAD software and AutoLISP language. User receives recommendations or outputs though user interface either on AutoCAD screen or VB forms. The user is also guided in a friendly manner throughout the consultation on how to proceed further after execution of each module. The proposed system is implemented on PC (Pentium 4 CPU, 2.0 GHz, 2 GB RAM) with Autodesk AutoCAD software.

4.2 Organization of the Proposed System

The proposed system labeled as INTDDD has been organized into various subsystems and modules. Organization of the system is shown in Fig. 2 (Naranje and Kumar 2014a). Execution of the various subsystems and modules are briefly described as under.

4.2.1 Subsystem PPDDP

The subsystem namely PPDDP is developed for process planning of axisymmetric deep drawn parts (Naranje and Kumar 2013a, 2014b). The system consists of three modules namely BLDIA, PROCPAR and DRWSEQ. The system PPDDP assists the process planers and die designers of stamping industries for calculation of blank

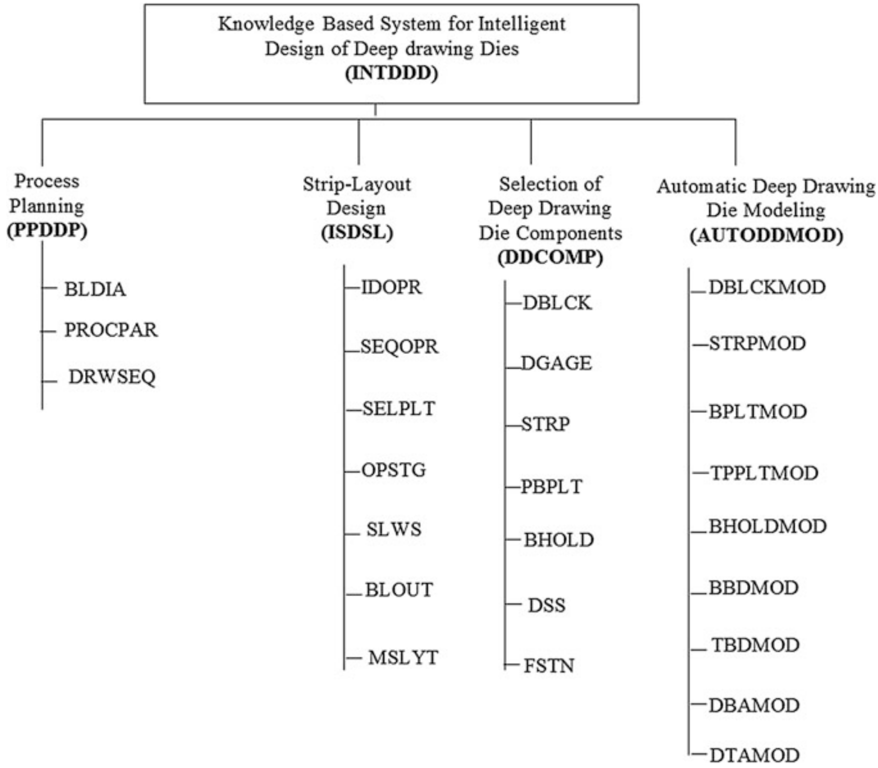
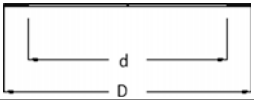
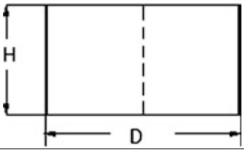
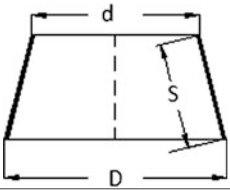
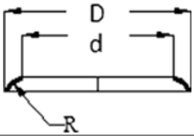
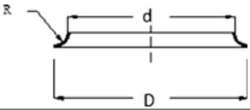
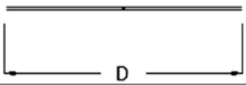


Fig. 2 Organization of the proposed knowledge-based system

diameter, selection of process parameters, and development of process sequence for axisymmetric deep drawn sheet metal parts.

For development of module BLDIA, a feature library of axisymmetric deep drawn parts is constructed for part modeling and blank size calculation. It consists of various primitives shapes such as ring, cylinder, taper, convex, concave, disk, etc. Various shapes of part features and the mathematical formulas for calculation of their surface area stored in this feature library are listed in Table 2. A trim allowance is also considered to compensate the thinning and thickening of material during deformation. Production rules incorporated in the module are coded in AutoLISP language. Execution of the module BLDIA is depicted in Fig. 3. On loading the module through a graphical user interface (GUI), drawing editor window of AutoCAD displays feature library on AutoCAD screen. The module invites the user to select the primitives required to model the part geometry and then to enter the dimensions of selected primitives. The dimensions of selected primitives are stored in a data file labeled as PARTDIM.DAT. After selection of all the required primitives from feature library, the module models the part geometry in the drawing editor of AutoCAD and calculates its surface area and blank diameter.

Table 2 Feature library of axisymmetric deep drawn sheet metal parts

S. No.	Shape of part feature	Feature name	Surface area of feature
1		Ring	$A_{ring} = \pi/4(D^2 - d^2)$
2		Cylinder	$A_{Cyl} = \pi DH$
3		Taper	$A_{tap} = \pi(D+d)/2 * s$
4		Concave	$A_{Con} = \pi/4(2\pi RD + 8R^2)$
5		Convex	$A_{cov} = \sqrt{d_1^2 + 6.28rd_1^2 + 8r^2}$
6		Disc	$A_{disc} = \pi D$

The calculated blank diameter with/without trimming allowance is stored in a data file namely BLDIA.DAT and part drawing is stored in a drawing file labeled as PARTMOD.DWG.

The module PROCPAR is developed to determine the appropriate values of various process parameters. Module displays the output in the form of appropriate values of drawing force, blank holding force, draw measures, clearance, type of lubricant, draw speed, air vent size, etc., which are automatically stored in an output data file PROCPAR.DAT.

The module DRWSEQ is developed to assist die designers and process planners for the determination of suitable draw sequence for manufacturing of deep drawn parts. This module generates a sequence plan on the basis of geometric profile characteristics of the parts and formability of sheet material. The module is designed to take required inputs such as production requirement and tolerance on the part automatically from the part data file PART.DAT and various process parameters from PROCPAR.DAT. The user is also invited to enter other required inputs such as type of press, diameter of upper cylindrical section, height of lower

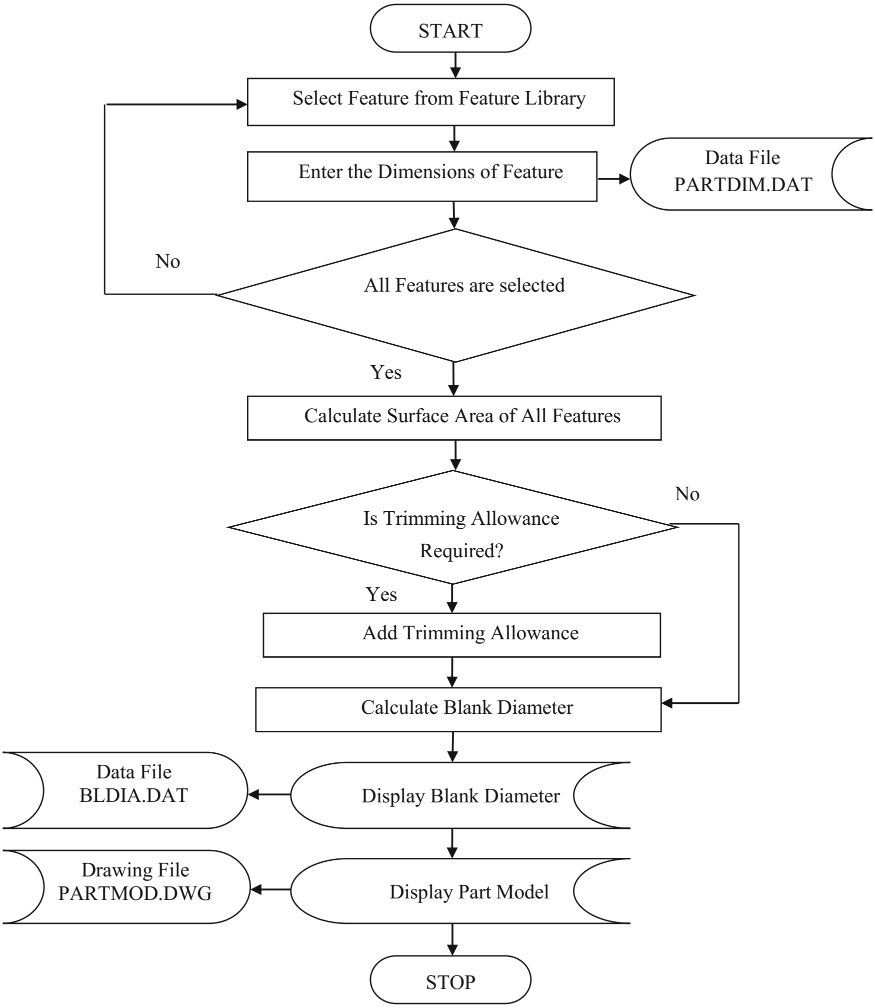


Fig. 3 Execution of module BLDIA

cylindrical section, length of taper section, etc., through graphic user interface (GUI). As soon as the user enters all required inputs, the module generates the process sequence on AutoCAD screen which is stored automatically in a drawing file DRWSEQ.DWG. The data related to draw sequence at each stage of deep drawing is stored in a data file namely DRWSEQ.DAT.

4.2.2 Subsystem ISDSL

The subsystem ISDSL is developed for design of strip-layout for production of axisymmetric deep drawn parts (Naranje and Kumar 2013b, 2014b). The proposed system has seven modules namely, (i) module IDOPR for identification of operations, (ii) module SEQOPR for sequencing of operations, (iii) module SELPLT for selection of piloting scheme, (iv) module OPSTG for staging of operation, (v) module SLWS for selection of strip size, (vi) module BLOUT for modeling of blank layout and (vii) module MSLYT for modeling of strip-layout in the drawing editor of AutoCAD. The execution of proposed system is shown in Fig. 4.

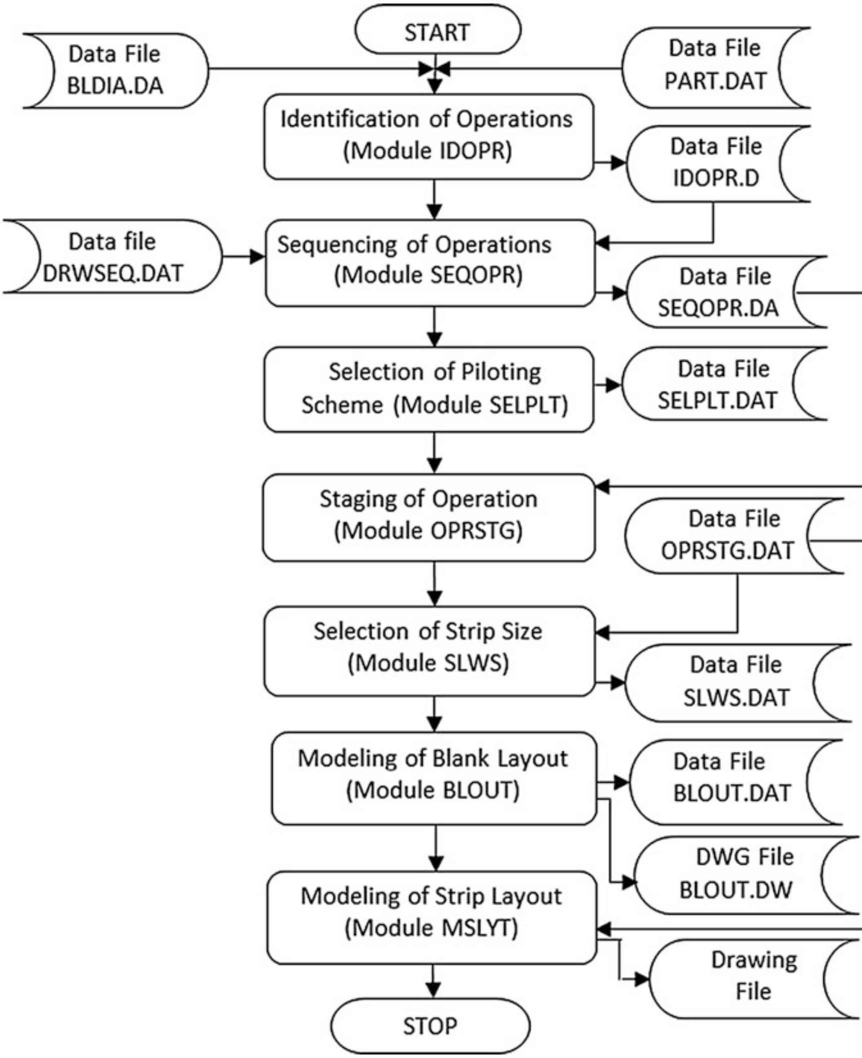


Fig. 4 Execution of subsystem ISDSL

4.2.3 Subsystem DDCOMP

The subsystem DDCOMP is developed for selection of major components of deep drawing die. The system is structured in form of eight modules, namely (i) module DBLCK for selection of size of die block, (ii) module DGAGE for selection of size of die gages, (iii) module STRP for selection of stripper, stripper plate, (iv) module PUNSEL for selection of punch details, (v) module PBPLT for selection of size of punch plate and backup plate, (vi) module BHOLD for selection of size of blankholder, (vii) module DSS for selection of type and size of die-set, and (vii) module FSTN for selection of fasteners.

The execution of proposed system is shown in Fig. 5 (Naranje and Kumar 2012, 2014a).

4.2.4 Subsystem AUTODDMOD

The subsystem AUTODDMOD is developed for automatic modeling (2-D and 3-D) of deep drawing die components and die assembly in the drawing editor of AutoCAD (Naranje and Kumar 2013c, 2014a). The proposed system consists of nine modules namely, (i) module DBLCKMOD for modeling of die block, (ii) module STRPMOD for modeling of stripper plate, (iii) module BPLTMOD for modeling of back plate, (iv) module PPLTMOD for modeling of punch plate, (v) module BLNKHMOD for modeling of blank holder, (vi) module BBDSMOD for modeling of bottom bolster of die-set, (vii) module TBDSMOD for modeling of top bolster of die-set, (viii) module DBAMOD for modeling of die bottom assembly, and (ix) module DTAMOD for modeling of top assembly of deep drawing die.

The outputs of various modules developed for selection of die components are recalled automatically during execution of the proposed subsystem. Execution of the proposed subsystem is depicted in Fig. 6. The first module namely DBLCKMOD takes required inputs in form of type and size of die block and fasteners from output data files generated during the execution of modules developed earlier for selection of design of die block and selection of fasteners. This module also recalls the drawing file of strip-layout labeled as MSLYT.DWG generated during execution of strip-layout module. The module is capable to generate 2-D and 3-D drawings of die block automatically in the drawing editor of AutoCAD software. The module is designed to save the top and front views of die block automatically as a global block, namely, WDBLCKMOD for its further use in modeling of die assembly. The module namely STRPMOD is constructed for automatic modeling of stripper plate. Inputs in form of size of stripper plate and fasteners are read automatically from the data files namely STRP.DAT and FSTN.DAT, generated during the execution of module developed earlier respectively for selection of stripper and selection of fasteners. The output of this module is in the form of 2-D and 3-D drawings of stripper plate is automatically stored in output global block, namely, WSTRPMOD in '.DWG' format. The next module namely BPLTMOD is developed to model top and front views of back plate of deep drawing die. The module takes its input in form

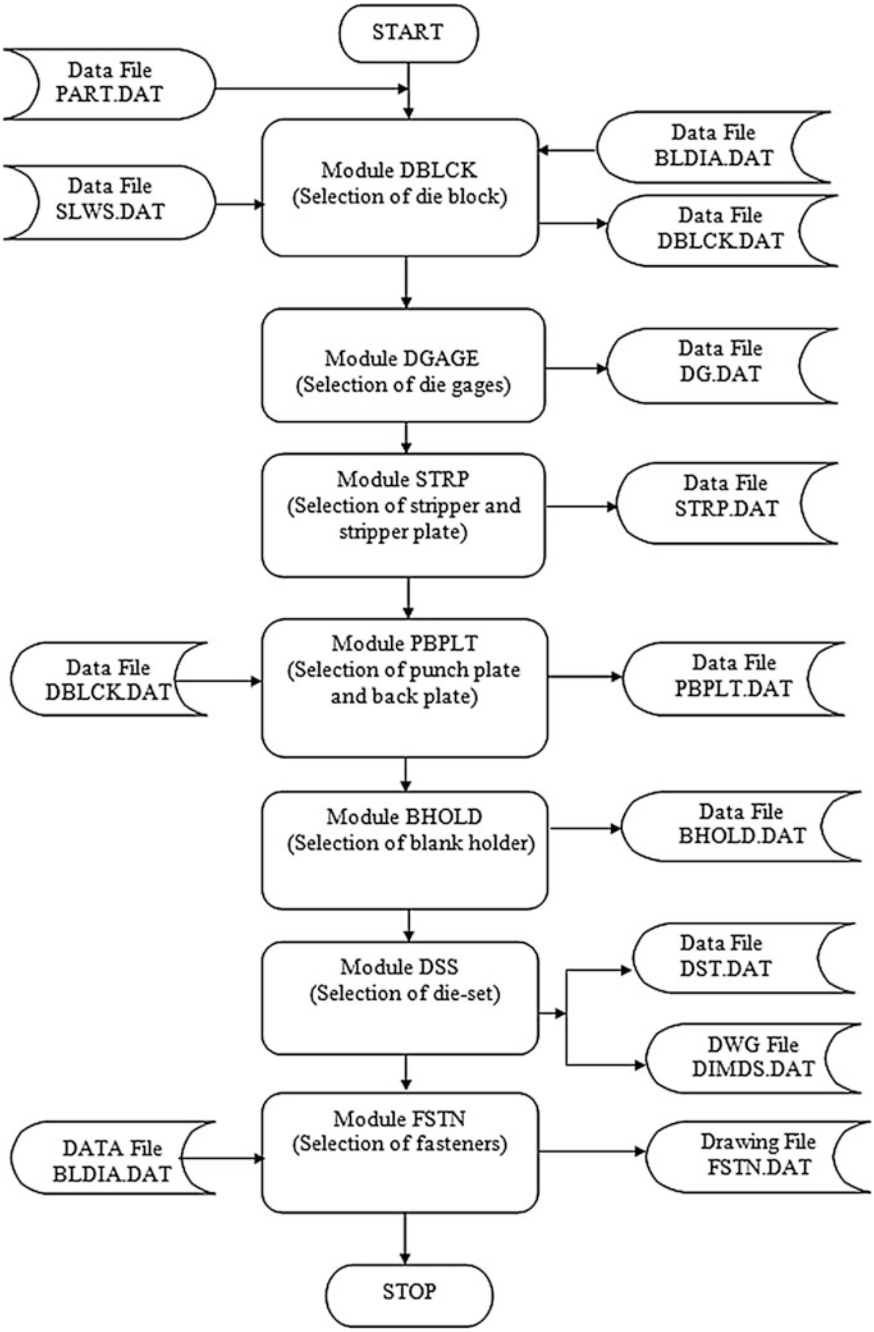


Fig. 5 Execution of the subsystem DDCOMP

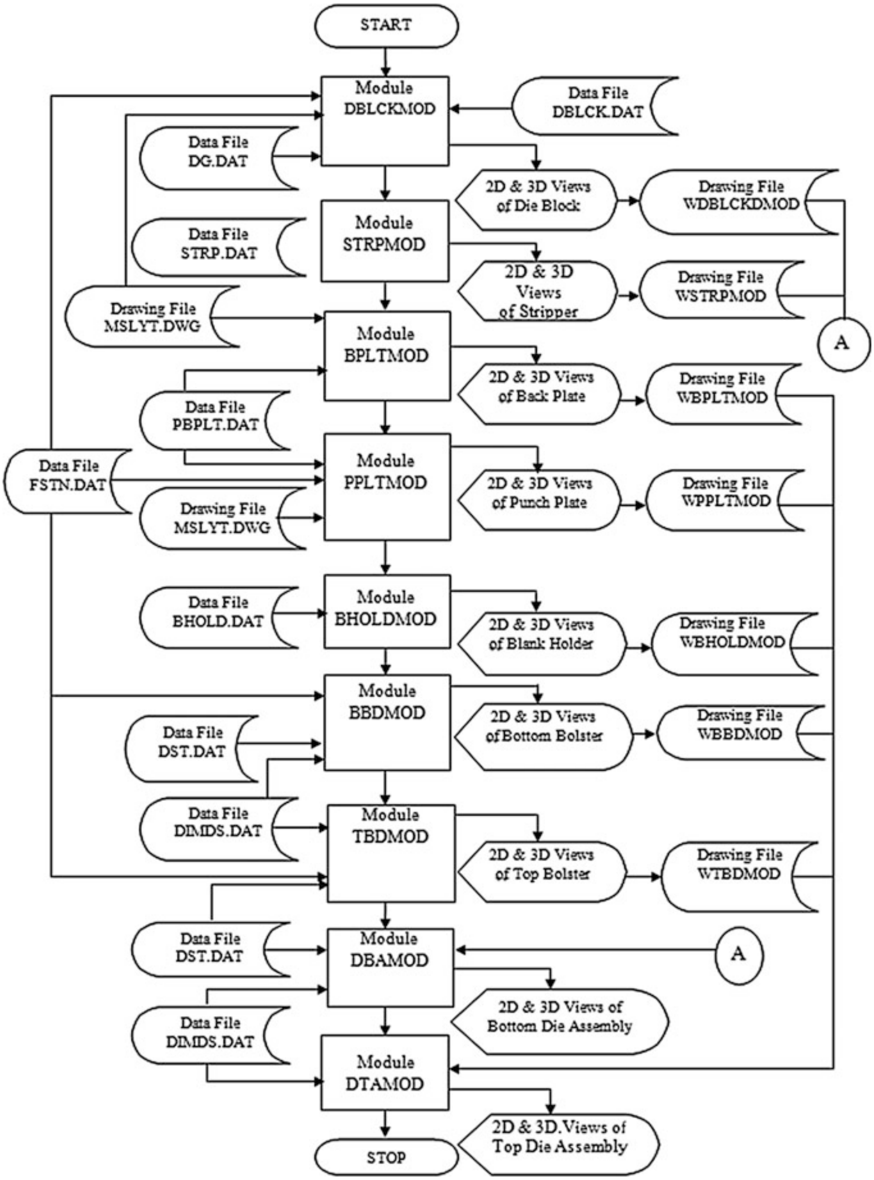


Fig. 6 Execution of the system AUTODDMOD

of dimensions of back plate from the data file PBPLT.DAT and fastener data from the data file FSTN.DAT. Output of this module includes orthographic and 3-D view of back plate and are automatically saved as a global block namely WBPLTMOD. The module labeled as PPLTMOD is developed to model punch plate automatically in the drawing editor of AutoCAD.

Similar to previous module, this module also takes inputs directly from output data file PBPLT.DAT and FSTN.DAT. The outputs of the module in the form of orthographic and 3-D view of punch plate are automatically saved as a global block namely WPPLTMOD. The next module namely BHOLDMOD of the system has been designed to model blank holder of deep drawing die. It recalls the data file BLHOLD.DAT to read size of blank holder. The outputs of this module in the form of orthographic and 3-D view of blank holder are automatically saved as a global block namely WBHOLDMOD. The modules labeled as BBDMOD and TBDMOD are developed, respectively, for automatic modeling of bottom bolster and top bolster of die-set of deep drawing die. These modules recall data files namely DST. DAT, DIMDS.DAT, and FSTN.DAT to take inputs in the form of type of die-set, its dimensions and size of fasteners.

The drawings of bottom bolster and top bolster generated by these modules are automatically saved as global blocks, respectively, labeled as WBBDSMOD and WTBDSMOD. These can be recalled during the modeling of die assembly. The next module namely DBAMOD is developed for automatic modeling of bottom assembly of deep drawing die. The bottom assembly consists of bottom bolster, die block, and stripper plate. The module reads the data from data files DST.DAT and DIMDS.DAT. On the basis of type of die-set, it computes the reference point on die-set for inserting global blocks of die block and stripper plate. Next, it inserts the global blocks of die block and stripper plate generated during execution of previous modules relative to the bottom bolster on the calculated reference point. The complete dimensioned orthographic views of bottom die assembly are automatically saved as a drawing file namely DBAMOD.DWG. The last module namely DTAMOD of the proposed system is developed for automatic modeling of the top assembly of deep drawing die. The module recalls the data files DSS.DAT and DIMDS.DAT to read type of die-set and their dimensional details. Next, it recalls the global block of top bolster of die-set and inserts the global blocks of back plate and punch plate on the calculated reference point. The 2-D and 3-D views of top die assembly are automatically saved as DTAMOD.DWG.

5 Validation of the System INTDDD

The developed system INTDDD has been tested for various types of industrial deep drawn sheet metal parts for design of deep drawing die. A sample run of the system modules for one typical deep drawn part (Fig. 7) is depicted in Figs. 8, 9, 10, 11, 12 and 13. The outputs of various system modules are found to be reasonable and very similar to those actually practiced by domain experts in industry (namely M/s GEC Private Limited, Pune, India) for the example part. The proposed system has also been tested successfully in other sheet metal industries including M/s Shrys Tool Makers, Pune, M/s Hindustan pressings Pvt. Ltd., Pune, M/s Allwin press tools, Pune, M/s G & G Engineering, Pune, and M/s Nirmiti Stampings Pvt. Ltd. Pune, India for various types of axisymmetric deep drawn sheet metal parts. The outputs

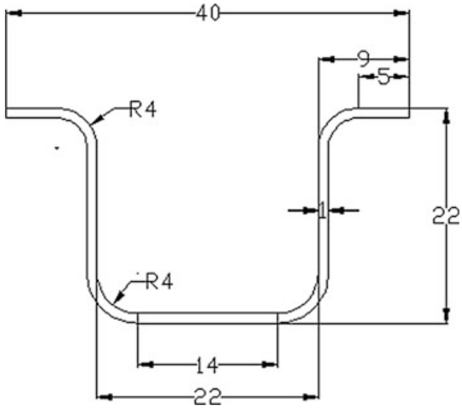


Fig. 7 Example part (all dimensions in mm; Sheet material: M.S, Sheet thickness: 1.0 mm)

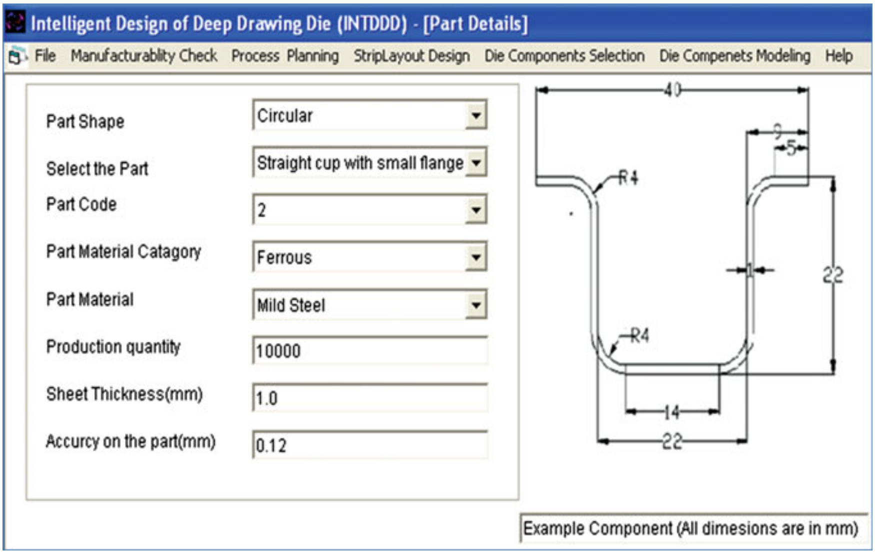


Fig. 8 User interface of proposed system INTDDDP

generated by the proposed system for various types of axisymmetric deep drawn parts were found very similar to that developed by the domain experts in these industries. The proposed system is capable to execute the design task of deep drawing die in less than 45 min. Also notable feature of the proposed system is its low cost of implementation because it can be implemented on a PC having AutoCAD software. Further, knowledge base of the system is flexible enough to accommodate new knowledge or editing of existing knowledge easily due to advancement in sheet metal technology in the future (Fig. 14).

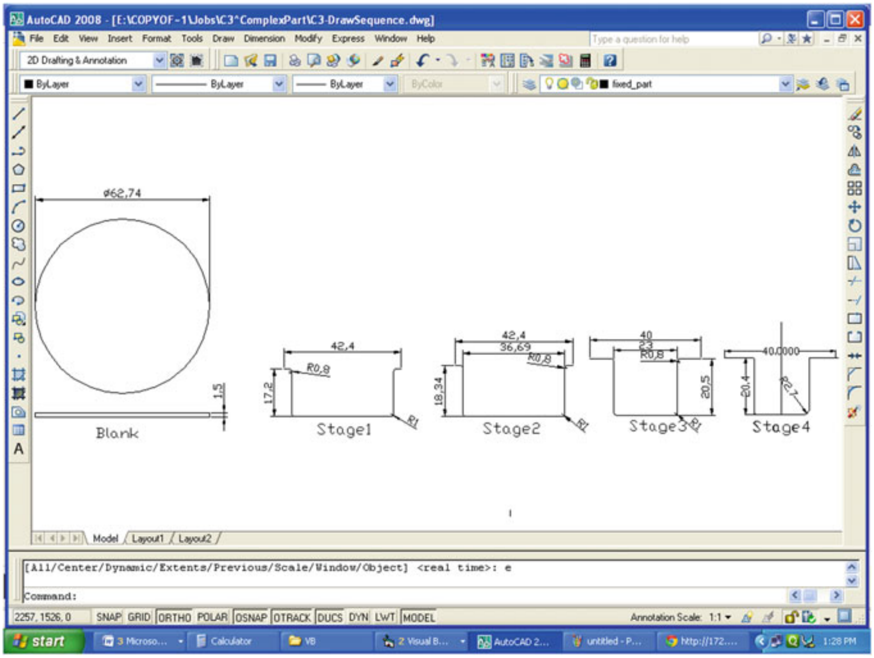


Fig. 9 Output of DRWSEQ module for example part

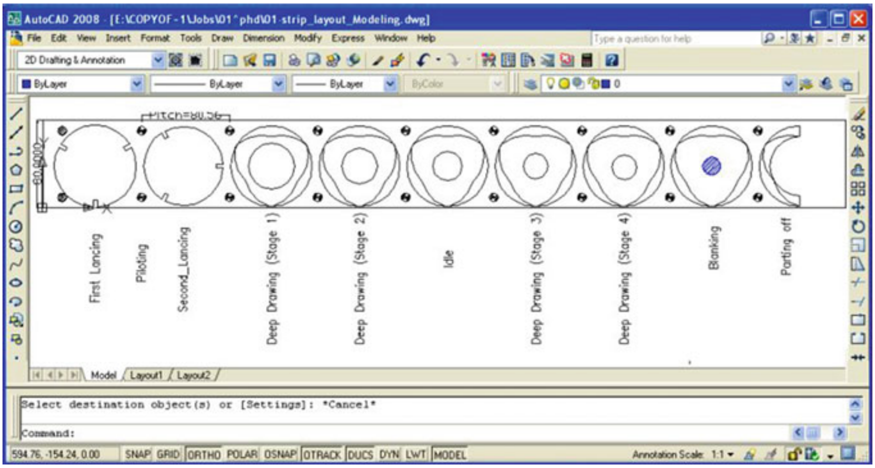


Fig. 10 Output of MSLYT module for example part

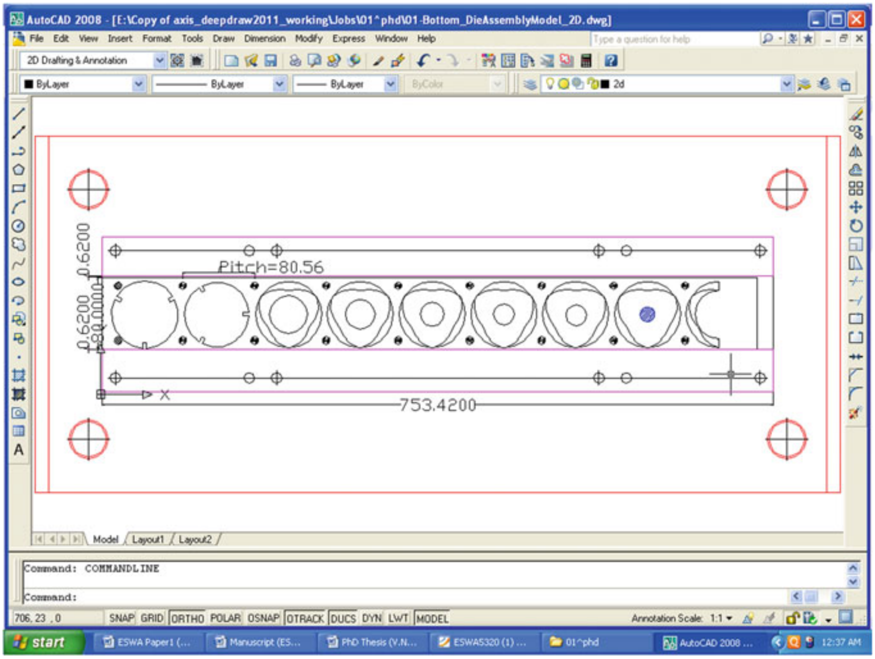


Fig. 11 Output of DBAMOD module (2-D drawing of bottom die assembly for example part)

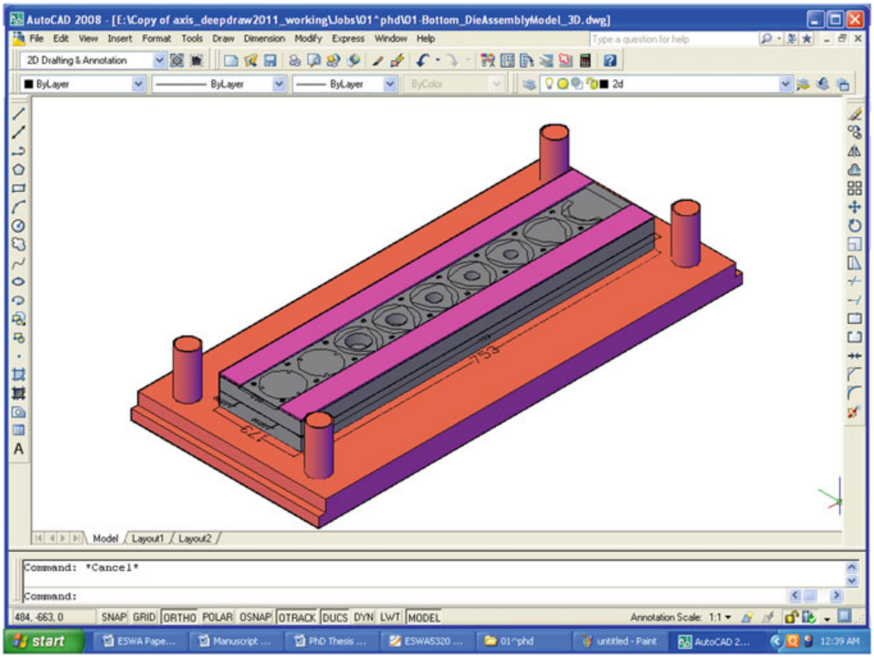


Fig. 12 Output of DBAMOD module (3-D drawing of bottom die assembly for example part)

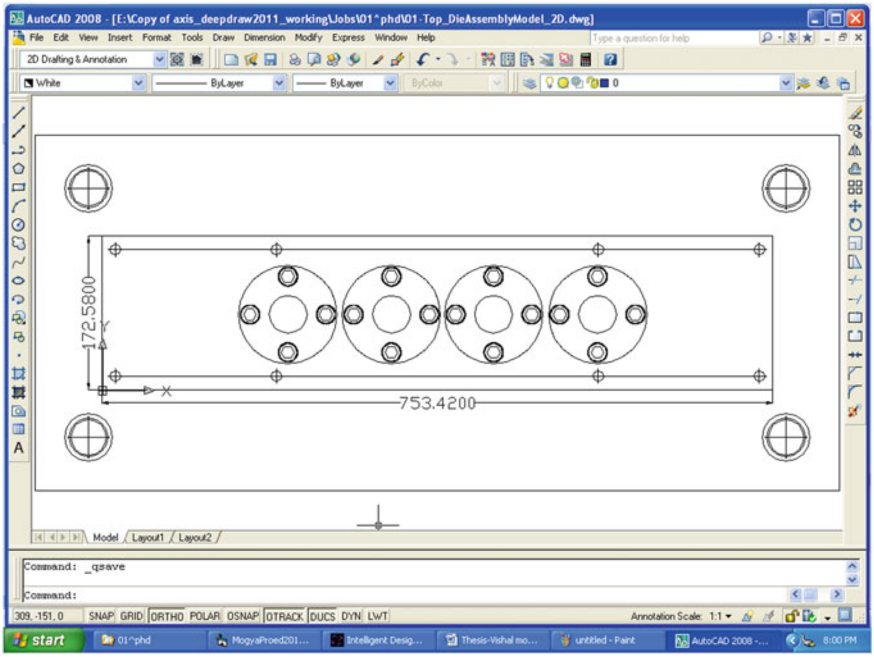


Fig. 13 Output of DTAMOD Module (2-D drawing of bottom die assembly for example part)

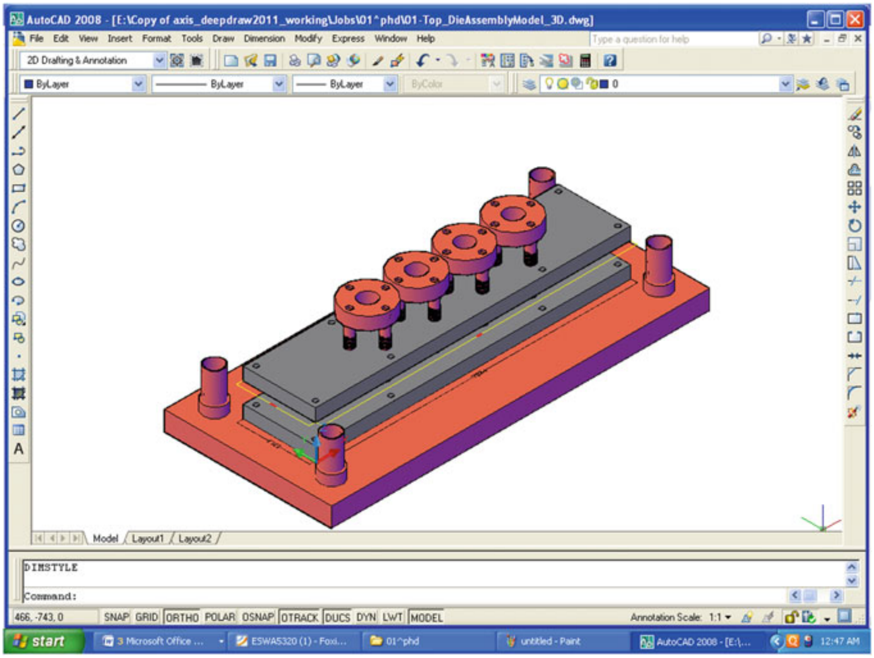


Fig. 14 Output of DTAMOD Module (3-D drawing of bottom die assembly for example part)

6 Conclusion

This chapter is focused on automatic design of deep drawing die for axisymmetric parts. Problems in traditional process of die designs are highlighted and then R&D efforts applied by worldwide researchers in this domain are discussed. A knowledge-based system developed by authors for design of deep drawing dies for axisymmetric parts is described. The developed system consists of more than 1000 production rules of 'IF-THEN' variety. To construct the knowledge base of proposed system, these rules are coded in AutoLISP language and user interface is created using Visual Basic 6.0 on AutoCAD platform. The system has been tested for various types of industrial axisymmetric deep drawn parts. Recommendations imparted by the system modules for process planning, strip-layout design, selection of die components, and the drawings generated by the system were found to be reasonable and very similar to those actually practiced in stamping industries. The developed system is capable to execute the whole task of deep drawing die design in less than an hour. The system can be implemented on a PC having AutoCAD software and therefore its low cost of implementation makes it affordable by small and medium scale sheet metal industries. Further, the system is flexible enough as its knowledge base can be extended or modified easily on the advancement of technology in sheet metal industries.

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An Integrated Approach for Optimized Process Planning of Multistage Deep Drawing

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1 Introduction

Deep drawing is the process in which a sheet metal blank is drawn in a hollow cavity (die) using a normal force applied by the punch to produce a hollow shell. A blank holder is used to control and guide the flow of the blank material through applying the blank holder force. Due to drawability limitations of the blank sheet material, several drawing stages may be needed before the required shape and dimensions of the final product can be obtained. Heat treatment may also be needed during the process in order to restore the formability of the material so that failure is avoided. A subtle process plan should seek minimizing the number of drawing stages and heat treatments needed in order to reduce manufacturing costs and lead time.

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The multistage deep drawing process has gained increasing interest in the literature toward optimizing its parameters and developing computer-aided process planning (CAPP) systems. Within such systems, artificial intelligence (AI) plays an important role as it is involved in recognizing final part shape, optimizing process parameters and recommending valid process plans. The rest of this chapter is organized as follows.

Section 2 presents a literature review on the CAPP systems developed for the deep drawing process and the role of AI tools therein. In Sect. 3, a general layout of the suggested AI approach is provided. This is followed in Sect. 4 by the developed final part shape recognition procedure. The technical rules and constraints governing the process design of multistage deep drawing process are summarized in Sect. 5. In Sect. 6, details of the developed optimization framework for minimizing the number of drawing and heat treatment stages are shown. Feasible optimized process plans are validated by careful finite element analysis (FEA), and this section shows crucial technical considerations relevant to such FEA. In Sect. 7, two illustrative case studies are presented to demonstrate the effectiveness of the proposed integrated approach. This is followed by the concluding remarks in Sect. 8.

2 Literature Review

Process planning is an important component of the manufacturing system as it represents the bridge between engineering design and manufacturing. In process planning, all necessary steps required to execute a part in a manufacturing process are defined and a set of instructions to be followed in converting the work part from raw material into a finished part are prepared. A computer-aided process planning (CAPP) system serves as a link between computer-aided design and computer-aided manufacturing. It is basically the application of computers to assist the human process planner in the process planning functions. Having given the data of the components or the part to be manufactured, the CAPP system can generate a sequenced set of instructions used to manufacture the required part (Weill et al. 1982; Wang and Li 1991; Zhang and Alting 1994). The process planning for deep drawing involves several tasks including the calculation of the blank dimensions of the drawn part, the determination of the number of stages required to produce the part, geometry calculations for the part and tooling after each stage, determination of the need of the drawn part for annealing after each stage, and also appropriate selection of the lubricant and drawing speed for the process.

Artificial intelligence plays an important role in CAPP systems for deep drawing. An expert system integrates the knowledge related to the technical requirements gained through experience and analysis into a rule base (RB) system. RB system is important for quick and effective selection of process parameters. Final part shape recognition is necessary to determine initial blank shape and its dimensions. Search, optimization, and process validation are necessary for optimizing process parameters and for making sure that their values will generate successful process plans that can be implemented.

In a rule base system for deep drawing process, the essential technical knowledge and calculation required for process design and planning are extracted from plasticity theories, relevant references, and empirical knowledge of experts in deep drawing. This technical knowledge is represented in the form of IF–THEN statements. The main advantage of RB systems is the ease of implementation, modification, and learning (Sitaraman et al. 1991).

The first serious attempt to develop a RB system for axisymmetric deep drawing of monotonic parts was probably that due to Eshel et al. (1986). They presented contemporary basic metal flow pattern and mathematical formulation of the deep drawing process in a rule form and suggested a reasonable tactic for rule-based automatic reasoning called generate and test-and-rectify (G & TR) for rectification or generation of another plan. An RB approach was also applied by Sitaraman et al. (1991) for developing the process sequence design system in axisymmetric sheet metal forming. Sing and Rao (1997) used decision tables to represent a knowledgebase system for axisymmetric deep drawing process, whereas an artificial intelligent (AI) technique was developed by Fang and Tolouei-Rad (1994) using LISP language in the environment of AutoCAD. RB systems with emphasis on tool design of multistage drawing of round parts were developed by Fogg (1996), Choi et al. (2000), and Park et al. (2002). An efficient CAPP system should use a convenient method to recognize the drawn part shape. Although the automatic feature recognition approach was successfully used in machining processes for long time (Han and Rosen 1998; Ramesh et al. 2000), it seems that it was not that much developed for deep drawing until recently. In the CAPP system of Tisza (1998), part geometry is selected from graphical menu according to its morphological shape. The graphical menu includes most of primitive shapes of axisymmetric parts. Park (1997) and Park et al. (1998) used the concept of "shape list" for recognizing part geometry. In a shape list, the data of the primitive shapes (e.g., shape and name of the basic entities, lines and arcs, and the geometry of these entities) of the part are input by the user. Later, Park et al. (2002) used 3-D modeling features in AutoCAD using AutoLISP to calculate surface areas of the drawn parts. An expert system for process planning of sheet metal forming with progressive dies has been presented by Vosniakos et al. (2005), in which three modules namely part design, process planning, and tool design are included. Zhang et al. (2006) developed a CAPP system for multistage of non-axisymmetric sheet metal deep drawing parts. This system used case-based reasoning (CBR) approach and is implemented in a C-language integrated production system (CLIPS) and interfaced with the solid edge computer-aided drafting (CAD) system. Wifi et al. (2004, 2005, 2008) developed a RB computer-aided process planning system, namely DRAW–CAPP. Round- and box-shaped parts are considered in this system. A procedure is also developed for the drawing of conical parts. The developed system is coded using Visual Basic (VB) to report the load and tooling requirements and is interfaced with AutoCAD to plot the shape of the drawn shell in each stage of the deep drawing process. A CAPP system based on the experimental results and empirical knowledge of experts for axisymmetric deep drawn parts has been proposed by Abbassi et al. (2007). The system is coded in VB under platform of AutoCAD system. A knowledge- based system for automatic calculations of stamping process parameters for design of stamping dies has been developed by Potocnik et al. (2011, 2012). This system was integrated in CATIA V5, and coded using inbuilt language. Recently, Naranje and Kumar (2014) developed a knowledge-based system for automated design of deep drawing die for axisymmetric parts. The system is coded in AutoLISP language and user interface is created using Visual Basic 6.0 and AutoCAD software.

Search and optimization for the deep drawing process is an important AI tool that targets the selection of optimum process parameters in order to improve the quality of the final product and/or the economics of the process. Wifi et al. (2007) presented a literature review on the different optimization techniques used in the deep drawing process, where they classified them into two main categories. The first one, started in the early 1980s, uses rules-of-thumb to determine optimized process parameters that would improve the output of the process. The second one, introduced in the early 1990s, is more systematic as statistical techniques are implemented. These techniques present an optimization methodology in the form of an online algorithm in which search directions are determined and regularly updated as the outcomes of the process are revealed. In both approaches, a real experiment is conducted and/or a simulation software package that implements the finite element method (FEM) is used to validate the process and to assess the benefit from the optimization approach or the proposed selection of process parameters.

Recently, Abdelmaguid et al. (2011, 2012, 2013) presented an optimization approach based on dynamic programming to minimize the number of drawing stages and heat treatments in multistage deep drawing of both box-shaped parts and cylindrical shells. The dynamic programming approach utilizes process design rules to define the search space for part dimensions at each stage, which is then optimized to achieve the stated objective. Validation and final selection of optimized process plans are conducted via FEA. Wifi and Abdelmaguid (2012) discussed a general framework for optimized process design of multistage deep drawing. In the framework, optimization of every aspect of the process design is taken into consideration including tooling and blank holding force, blank shape as well as process planning.

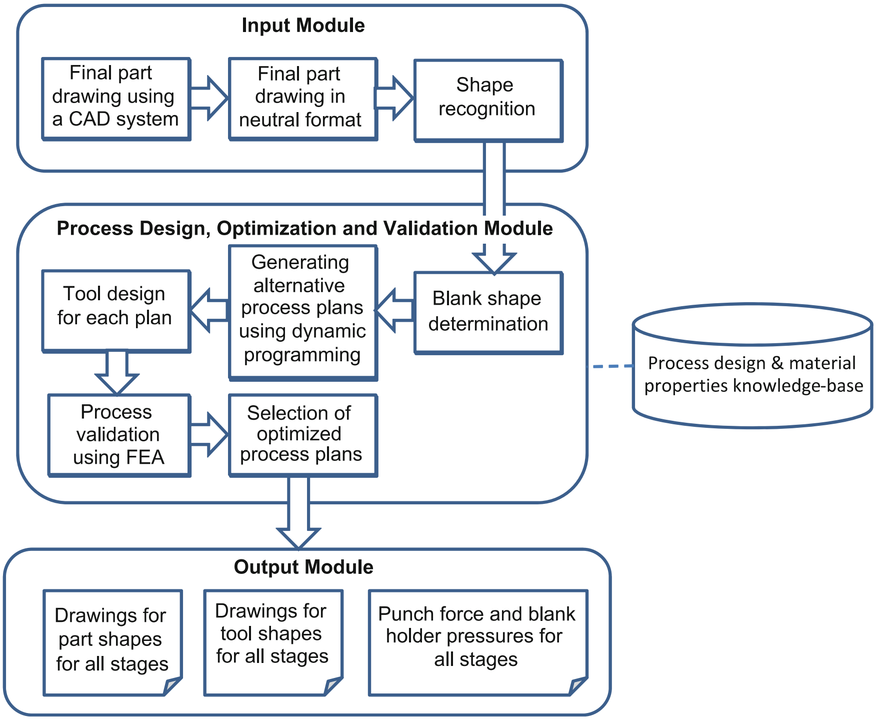


Fig. 1 Schematic diagram for the developed integrated AI approach

The present work elaborates and integrates the recent contributions of the authors on process planning and optimization of multistage deep drawing process design. The elements of the integrated approach include shape recognition of the final part (Wifi et al. 2004, 2005), part shape determination at each drawing stage with the objective of minimizing the number of drawing stages and heat treatments using dynamic programming (Abdelmaguid et al. 2011, 2012, 2013), and process validation and selection of optimized process parameters using FEA (Wifi et al. 2010).

3 Integrated AI Approach

Figure 1 illustrates the general framework of the developed integrated approach which starts with an input module in which final part drawings are received from user's input via a suitable CAD system. This input is converted into a neutral format for easier interpretation of the part shape. A shape recognition module is then used to decompose the neutral format into primitive geometrical elements whose areas can be easily determined. The calculation of the total area is necessary to determine the initial blank shape.

The process design and optimization module, which is the main computational module of the developed AI approach, starts with calculating the required blank shape and its dimensions based on the information generated by the input module. Here, material properties along with theoretically or empirically determined process design rules are used as the knowledge base that provides guidance to the developed computations and optimization methods herein. These computations involve generating alternative process plans using dynamic programming which guides the selection of the shape and the dimensions of the intermediate parts so as to minimize the total number of drawing stages and heat treatments needed. They also involve the selection of the dimensions of the tools and suitable values for the blank holder pressure and punch force for each drawing stage to ensure the success of the process. Finite element analysis (FEA) and simulation are used to validate those selections. Results from FEA are studied by the decision maker at the next step which requires human intervention to select a set of optimized process plans that satisfy his/her criteria. Such criteria may include thickness distribution along the walls of the final part or its strain severity condition.

The results of the selected optimized process plans and the details of the designs of intermediate parts and tools are then presented in the form of reports in the output module. These reports include drawings for part shapes and tool shapes throughout stages, along with reports for suitable values of the punch force and the blank holder pressure.

4 Shape Recognition

Figure 2 depicts the main steps of the shape recognition algorithm. The input to this algorithm is the 2-D drawing of the part which is stored in neutral format file (i.e., DXF, STEP, IGEAS, etc.). Relevant data to the shape recognitions are extracted from this file. For instance, in a DXF file, four sections are considered, namely header section, table section, block section, and entities section. The first three sections deal with the environment according to the CAD system used, while the last section (entities section) includes geometrical data of the drawn part. The basic entities considered in the entities section are line, arc, 3-D face, 3-D solid, circles, text, etc. The attributes of these basic entities are extracted from the neutral format file, and then their geometrical data are sorted. The dimensions of the basic entities

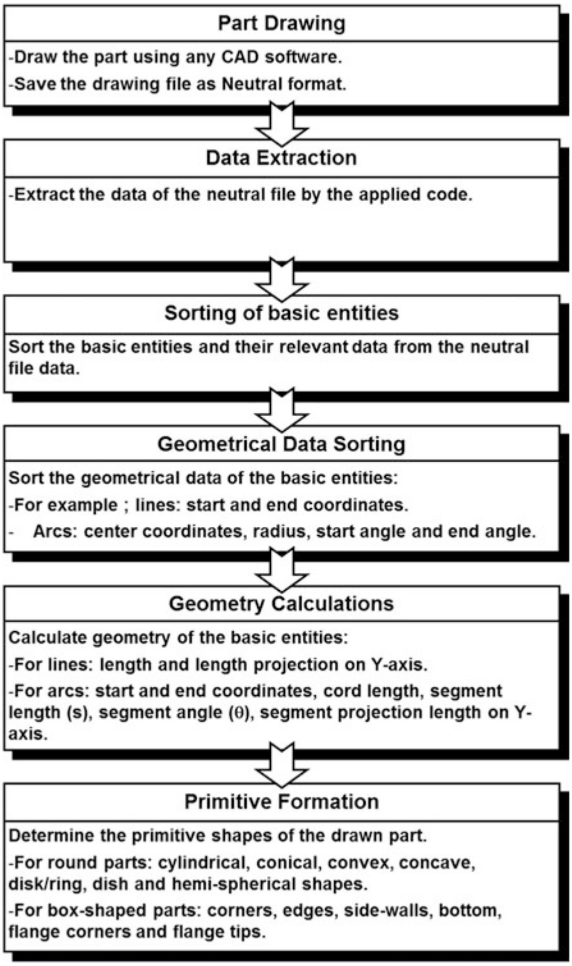


Fig. 2 Main steps of the shape recognition algorithm

are calculated and then the morphologies of the primitives of the drawn part are formed and recognized.

In the present AI approach, shape recognition module for box-shaped parts (square and rectangular) is developed. The part is represented by its top and front views in different layers, as shown in Fig. 3, using the boundary representation (B-Rep) method in 2-D to model the part drawing. A decomposition method is proposed for shape recognition by Shah and Mantyla (1995), in which the part is divided into their morphology of primitive shapes, as shown in Fig. 4. Table 1 shows the developed morphology of the primitive shapes of the box-shaped parts (i.e., corners, edges, bottom, sidewalls, flange corners, and flange strip) and the mathematical relations used for their surface area calculation.

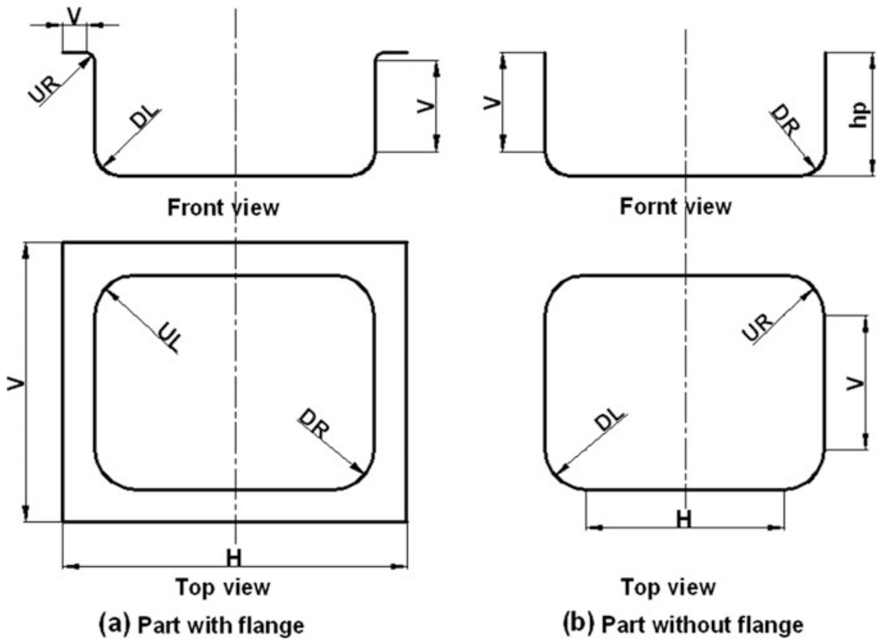


Fig. 3 Basic symbols for *box-shaped* part

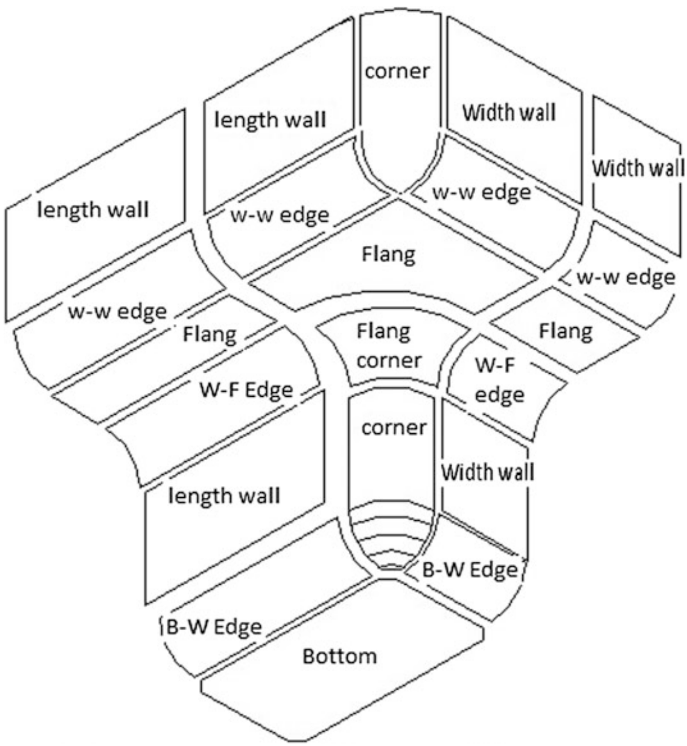
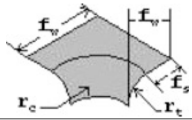
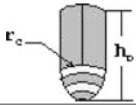
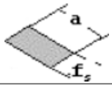
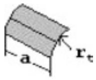
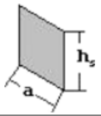
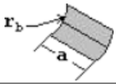
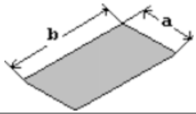
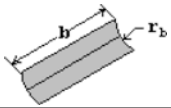
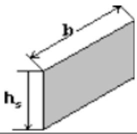
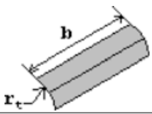
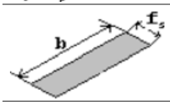


Fig. 4 Morphology and symbols used for part geometry recognition

Table 1 Developed primitive shapes of the box-shaped part

Primitive shape	Primitive name	Equation of surface area calculation
	Flange corner	$A_{fcr} = \frac{1}{4}\left[(2f_w)^2 - \frac{\pi}{4}(2r_c)^2\right]$ $f_w = f_s + r_t$
	Corner	$A_{cr} = \frac{1}{4}\left[\frac{\pi}{4}(2r_c)^2 + \pi(2r_c)h_p\right]$
	Width flange strip	$A_{wfs} = af_s$
	Width flange edge	$A_{wse} = \frac{1}{4}[\pi(2r_t)a]$
	Width side wall	$A_{wsw} = ah_s$ $\left(h_s = h_p - r_b - r_t\right)$
	Width bottom edge	$A_{wbe} = \frac{1}{4}[\pi(2r_b)a]$
	Bottom area	$A_{bot} = a \cdot b$ (in case $r_c = r_b$) $A_{bot} = a \cdot b + 2a(r_c - r_b) + 2b(r_c - r_b)$ (in case $r_c > r_b$)
	Length bottom edge	$A_{lbe} = \frac{1}{4}[\pi(2r_b)b]$
	Length side wall	$A_{lsw} = bh_s$ $\left(h_s = h_p - r_b - r_t\right)$
	Length flange edge	$A_{lfe} = \frac{1}{4}[\pi(2r_t)b]$
	Length flange strip	$A_{lfs} = bf_s$

With the assumption of constant sheet thickness during deep drawing, the surface area of the blank for flanged box-shaped part ($A_{p,0}$) equals the summation of the areas of its primitives as given in Table 1, which leads to Eq. (1) below:

$$
\begin{aligned}
A_{p,0} = {} & \left[\frac{\pi}{4}(2r_c)^2 + \pi(2r_c)(h_p - r_t)\right] + \left[\frac{\pi}{2}(2r_b)a\right] + \left[\frac{\pi}{2}(2r_b)b\right] \\
& + [a \cdot b + 2a(r_c - r_b) + 2b(r_c - r_b)] + [2a(h_p - r_b - r_t)] \\
& + [2b(h_p - r_b - r_t)] + \left[\frac{\pi}{2}(2r_t)a\right] + \left[\frac{\pi}{2}(2r_t)b\right] \\
& + \left[(2r_t)^2 - \frac{\pi}{4}(2r_c)^2\right] + [2a(f_w - r_t)] + [2b(f_w - r_t)]
\end{aligned} \tag{1}
$$

To calculate the surface area of the blank for flangeless part, we set $r_t = f_w = 0$ in Eq. (1). Trimming allowance should be added either to the flange of the box or to its height. Typical values of the trimming allowances are provided in Eary and Reed (1958).

By determining the dimensions of the basic entities that constitute the final part, the dimensions of the final part defined by length (l_p), width (w_p), height (h_p), bottom radius (r_b), and corner radius (r_c) can be calculated. Based on this, the length (L_B) and width (W_B) of the blank required are calculated as follows (Aida 1992; Suchy 1998).

$$L_B = b + 2\left[h_s + \frac{\pi}{4}(2r_b) + \frac{\pi}{4}(2r_t)\right] \tag{2}$$

$$W_B = a + 2\left[h_s + \frac{\pi}{4}(2r_b) + \frac{\pi}{4}(2r_t)\right] \tag{3}$$

The corner radius ($r_{c,0}$) of the blank required for flanged box-shaped part is calculated as follows (Wifi et al. 2005):

$$r_{c,0} = \sqrt{r_c^2 + 2r_c h_s + 1.14 r_c r_b - 0.14 r_b^2 + 3.14 r_c r_t + 1.14 r_t^2 + 4 r_c f_s + f_s^2} \tag{4}$$

For flangeless parts, we set $r_t = f_s = 0$ in Eq. (4). To avoid ear formation, corner areas of the blank are designed by following the procedures given by Newby (1976) and Smith (1990).

5 Process Design: The Governing Rules

This section provides details about the main technical rules that govern the selection of process parameters for box-shaped parts, which are necessary for the decisions that are implemented within the process design and optimization module of the integrated approach.

5.1 *Part Geometry in Drawing Stages*

Based on the determined blank shape and dimensions, as explained in the previous section, the dimensions of the part at any stage i, including corner radius, length, width, and height are governed by the technical rules presented in the following subsections.

5.1.1 Corner Radius

During drawing, the material behaves at the four corners of the box-shaped part as a cylindrical-shaped part (Sachs 1966). Therefore, the severity of the deep drawing of box-shaped parts is affected by the part corner radius (Wifi et al. 2005, 2008). Accordingly, the value of the part corner radius at a given stage i, denoted $r_{c,i}$, is governed by the drawing rate as represented by the following relationship:

$$m_n \leq \frac{r_{c,i}}{r_{c,i-1}} \tag{5}$$

where m_n is defined as the drawing rate limit and n is the number of drawing stages conducted since the last heat treatment is made. If l is the index of the last drawing stage after which a heat treatment is conducted, then $n = i - l - 1$. It is assumed that $n = 0$ when $i = 1$. The value of m_n is dependent on the type of material being processed. In Aida (1992), typical values of m_n have been determined for common materials used in deep drawing for both the first and second stages after heat treatment (i.e., m_0 and m_1). For the third and subsequent stages, the drawing rate limit has been approximated by Tisza (1998) as $m_n = m_{n-1} + 0.02$ for $n > 1$. Here, the initial corner radius ($r_{c,0}$) is provided earlier in Eq. (4).

Due to the deformation of the sheet metal during first and subsequent stages, the strain severity of the material increases. To avoid failure, the current strain severity should not exceed the strain severity limit which is based on material properties. If at any drawing stage the strain severity has become close to that limit, heat treatment must be conducted to restore the formability of the processed material. However, heat treatment may also be conducted after any drawing stage at a point that is not necessarily close to the strain severity limit depending on the decision maker's judgment which considers the remaining number of drawing stages.

At any stage i, the strain severity factor (ε_i) is calculated as $\varepsilon_i = \left[\left(r_{c,i-1}/r_{c,i}\right) + 1\right]/2$ for $i > 0$, while the cumulative strain severity (E_i) is given by $E_i = \prod_{j=l+1}^{i} \varepsilon_i$ for $i > 0$, where, as indicated earlier, l is the index of the last drawing stage after which heat treatment is conducted. The cumulative strain severity must not exceed the strain severity limit, denoted $E_{\max}$, which is based on the material properties. Therefore, the second constraint on selecting the post-drawing corner radius is expressed as follows:

$$E_i < E_{\max} \tag{6}$$

5.1.2 Cross Section

As suggested by Lange (1985), the rules that are used for calculating the drawing ratio in cylindrical shells can be used for drawing box-shaped parts by replacing the blank and punch areas with circular sections of equal size. This allows for using the following relationship:

$$\sqrt{\frac{A_{p,i}}{A_{p,i-1}}} = \bar{m}_n \tag{7}$$

In the above equation, $A_{p,i}$ refers to the part cross-sectional area at a given drawing stage i where $A_{p,0}$ is the initial blank area as provided in Eq. (1), and $\bar{m}_n$ is the resultant drawing rate based on the selection made for corner radii, i.e., $\bar{m}_n = r_{c,i}/r_{c,i-1}$. Meanwhile, the part cross-sectional area is calculated as follows:

$$A_{p,i} = l_{p,i} w_{p,i} \tag{8}$$

where $l_{p,i}$ and $w_{p,i}$ are the length and width of the part at stage i. Since the aspect ratio of the box-shaped part, which is defined by the ratio $l_{p,i}/w_{p,i}$, at stage i is recommended to be the same as the aspect ratio of the required final part, Eq. (8) can be solved to determine both values of $l_{p,i}$ and $w_{p,i}$.

5.1.3 Part Height

The height ($h_{p,i}$) at the end of stage i for the part is affected by the part geometry as well as the drawing rate as determined by the stage corner radius $r_{c,i}$. For flanged box-shaped part, the part height at stage i is calculated as follows (Wifi et al. 2010):

$$h_{p,i} = \left(\frac{A_f + 2\pi r_c r_t - a.b - (a+b)(2r_c - 2.43r_b - 2.43r_t) - 4(f_s + r_c)^2}{2(\pi r_c + a + b)} \right)_i \tag{9}$$

Equation (9) is very useful in calculating the height for each stage, which provides a guide for selecting the punch stroke length. Here, A_f is the product surface area. The values of a_i and b_i are, respectively, defined as $l_{p,i} - 2r_{c,i}$ and $w_{p,i} - 2r_{c,i}$. In Eq. (9), r_t is the wall flange radius (die profile radius), r_b is the wall bottom radius (punch nose radius), and f_s is the length of the straight part of the flange. For flangeless parts, we set $r_t = f_s = 0$.

5.2 Tool Design

Designs for the punch, the die, and the blank holder are determined based on the geometry of the part in each stage. The dimensions of the punch cross section (l_{punch}, w_{punch}), punch corner radius ($r_{\text{punch\_corner}}$), as well as the clearance between them are calculated as illustrated in the following subsections.

5.2.1 Punch Cross Section

The punch dimension for stage i is calculated based on the cross section dimension of the part as follows:

$$l_{\text{punch},i} = l_{p,i} - C \quad (10)$$

$$w_{\text{punch},i} = w_{p,i} - C \quad (11)$$

$$r_{\text{punch\_corner},i} = r_{c,i} - \frac{1}{2}C \quad (12)$$

where C is the clearance between punch and die which ranges from $1.1t$ to $1.5t$, and t is the initial sheet thickness.

5.2.2 Die Cross Section

Similarly, die cross section dimensions (l_{die}, w_{die}) and die corner radius ($r_{\text{die\_corner}}$) are calculated for stage i as follows:

$$l_{\text{die},i} = l_{\text{punch},i} + 2C \quad (13)$$

$$w_{\text{die},i} = w_{\text{punch},i} + 2C \quad (14)$$

$$r_{\text{die\_corner},i} = r_{\text{punch\_corner},i} + C \quad (15)$$

5.2.3 Die and Punch Nose Radii

The die radius (r_d) is usually determined either by empirical relations or by experience. In the current approach, a practical value of $r_d = 5t$ is suggested for all intermediate stages, whereas in the final stage, it is determined based on part geometry. The punch nose radius (r_p) should be more than the die radius with a factor ranging from $3t$ to $5t$; while in the final stage, it is equal to the radius of the bottom edge of the box.

5.2.4 Blank Holder Dimensions

As illustrated in Fig. 5, the blank holder dimensions are calculated based on the part dimension. In the current study, the blank holder is designed as a sleeve with inner and outer dimension. The inner dimension is equal to the die dimension of the current stage, while the outer dimension is equal to the dimension of the punch in the previous stage (except for the first stage, it is equal to the blank dimension).

5.3 Operating Parameters

5.3.1 Punch Force

The deformation resistance along the circumference of the box cross section is extremely high, since the corner with radius $r_{c,i}$ has radial and tensile stresses and

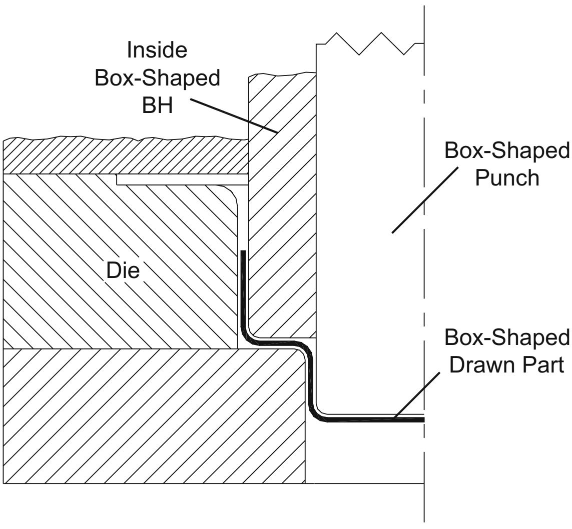


Fig. 5 Redrawing die for *box-shaped* parts with a sleeve (inside) blank holder

the straight portion of the sides with length $l_{s,i}$ has bending stress. Based on this analysis, the punch force ($F_{d,i}$) for box-shaped parts is calculated from empirical equation as follows (Sachs 1966; Aida 1992):

$$F_{d,i} = S_u t(2\pi r_{c,i} c_1 + l_{s,i} c_2) \quad (16)$$

Here, S_u is the ultimate tensile strength; $l_{s,i}$ is the summation of straight edges; c_1 equals 0.5 if operation is shallow drawing and equals 2 if the part height; $h_{p,i}$ equals from 5 to 6 times $r_{c,i}$; and c_2 equals 0.2 for ample clearance and no holding pressure and its value can reach up to 1.0 based on the difficulty of the drawing process.

5.3.2 Blank Holder Pressure

The blank holder force (F_{BH}) in deep drawing of box-shaped parts is higher than that required for drawing cylindrical parts, particularly if the draw beads are not allowed. It is difficult to determine the appropriate blank holder force; so it can be estimated as a percentage (10–30) % of the drawing force (Waller 1978). In the current approach, the blank holder force is assumed to one-third the punch force, i.e., $F_{BH,i}$ = ($F_{d,i}$/3). The blank holder pressure is determined approximately as follows:

$$P_{BH,i} = F_{BH,i}/A_{BH,i} \quad (17)$$

where $A_{BH,i}$ is the area on which the blank holder force is applied at stage i. It can be shown that the area of the blank holder for stage i is calculated as follows (Wifi et al. 2005):

$$A_{BH,i} = A_{\text{punch},i-1} - A_{\text{punch},i} - C(2l_{\text{punch},i} + 2w_{\text{punch},i}) \quad (18)$$

6 Optimization and Validation for Process Planning

Optimization and validation of the process plans is the most computationally expensive component of the developed AI approach. It is part of the process design and optimization module and it follows the blank shape determination component. It is sufficiently reasonable to assume that the determined blank shape is adequate enough to plan for a valid process, and there is no need to modify it due to unforeseen considerations that may appear during the process parameter selection and optimization.

The main concern of the process parameters selection and optimization component is to select appropriate values for the multistage deep drawing parameters that ensure the feasibility of the process and optimizes a predefined criterion. In the developed AI approach, the selected criterion is to minimize the number of drawing stages and heat treatments which improves the economics of the process. Recent contributions by Abdelmaguid et al. (2011, 2012, 2013) are provided for that objective, which are based on dynamic programming approach. In the following subsections, the main elements of the dynamic programming approach are presented.

6.1 Dynamic Programming Approach

Dynamic programming (DP) is a mathematical technique that is based on the idea of separating a decision making problem into smaller sub-problems. Each sub-problem represents a single stage whose solution is used to infer some properties that can be used to guide the solution of the other subsequent sub-problems (stages). The benefit of using dynamic programming is that it requires less computational effort compared to exhaustive enumeration in which all possible solutions to a given decision making problem are evaluated.

In an attempt to rationalize and optimize the process planning of multistage deep drawing for round or box shapes, Abdelmaguid et al. (2011, 2012, 2013) developed an integrated rule base–dynamic programming–finite element analysis (RB–DP–FEA) approach to generate alternative feasible process plans which minimize the total number of drawing stages and heat treatments. The plans with least strain severity are investigated by a comprehensive FEA with full account of formability and severity capabilities. The optimum plan is the one giving successful part with least severity, maximum thickness uniformity, and least risk of failure. Figure 6 presents the general scheme of the integrated RB–DP–FEA approach. To

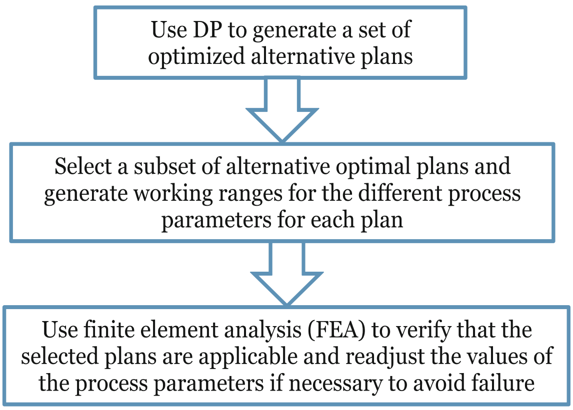


Fig. 6 General scheme for the integrated RB–DP–FEA approach

demonstrate this approach we consider only the box-shaped part. For cylindrical shells, the same analysis applies by replacing the corner radius (r_c) with the part diameter (d) in each stage. More details about the implementation of the RB–DP–FEA approach for cylindrical shells are provided in Abdelmaguid et al. (2013).

The stages in multistage deep drawing of box-shaped parts are defined by the specific part dimensions which are governed by the constraints and relationships presented in Eqs. (5), (6), and (7). These constraints define limits on part dimensions that need to be maintained to assure safety and success of the process. For the part area at a given stage, which is governed by constraint (7), there is flexibility in adjusting the values of the length and width, for which a wide range of values can be selected. However, the part corner radius, which is controlled by constraints (5) and (6), has less freedom and its selection is crucial for the process.

Let $\hat{r}_{c,i}$ denote the minimum corner radius at state i that is allowed by the two constraints (5) and (6). Figure 7 illustrates a traditional policy for selecting values for the corner radius ($r_{c,i}$) at each stage in which $r_{c,i}$ is set equal to $\hat{r}_{c,i}$. In case the final product corner radius ($r_{c,p}$) cannot be reached, annealing is conducted to restore the formability of the workpiece material.

Figure 8 illustrates the concept of flexible process plans in which an intermediate value of $r_{c,i} \leq \hat{r}_{c,i}$ can be selected at every stage with the possibility of conducting

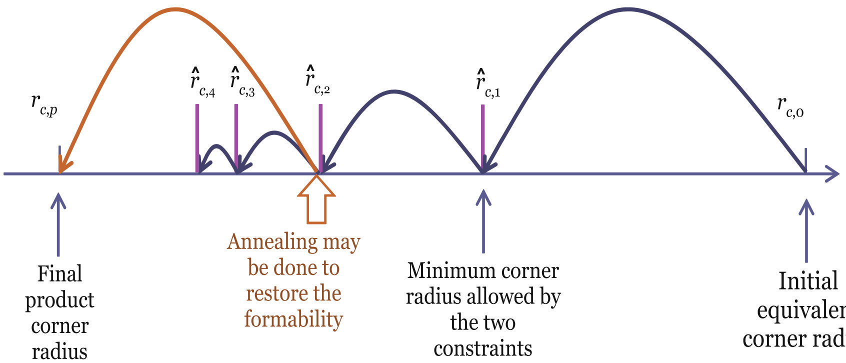


Fig. 7 Process plans exploiting full drawing limits

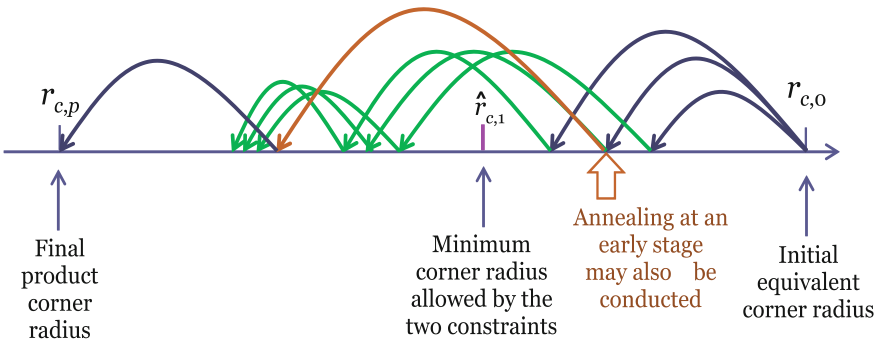


Fig. 8 Flexible process plans

annealing at an early stage. The idea behind flexible process plans is that with the requirement of heat treatment, the process plans that exploit the full flexibility as illustrated in Fig. 7 may be suboptimal since a heat treatment at an early stage can reduce the total number of drawing stages needed to reach $r_{c,p}$. Therefore, relaxing the condition of $r_{c,i} = \hat{r}_{c,i}$ with a more flexible condition of $r_{c,i} \leq \hat{r}_{c,i}$ allows for searching for an optimal process plan with the minimum number of drawing stages and heat treatments. However, this is not the only benefit of such flexible process plans as generating several alternative optimal plans allows a decision maker to choose the one that satisfies one or more other criteria. For instance, a decision maker may look at the thickness distribution of the final product and select the one that gives the most uniform thickness distribution.

Dynamic programming is found to be suitable for the studied problem as it reduces the number of evaluations needed for searching the values of $r_{c,i}$. In the DP implementation, the state at an arbitrary stage i, denoted $\mathbb{S}_i$, is defined by the tuple $\left(r_{c,i}, a_i, E_i\right)$, where $r_{c,i}$ is the resultant box corner radius, a_i represents the number of drawing stages conducted since the last heat treatment is made, and E_i is the cumulative strain severity up to stage i. The index of the initial state is set equal to zero where $\mathbb{S}_0 = (r_{c,0}, 0, 1.0)$, while there could be more than one terminal state for which the corresponding box corner radius equals $r_{c,p}$. The set of terminal states is defined as $\mathbb{T} = \left\{\left(r_{c,p}, a, E\right) : a \geq 1 \text{ and } E > 1.0\right\}$.

We seek to conduct the transition from state $\mathbb{S}_i$ to state $\mathbb{S}_j$ with the minimum possible number of drawings and heat treatments such that constraints (5) and (6) are not violated. We define $\Delta(\mathbb{S}_i)$ as a mapping from state $\mathbb{S}_i$ to the set of all feasible box corner radii that can be reached in a single drawing step. Accordingly, the set of such feasible states is defined as $\mathcal{F}(\mathbb{S}_i) = \left\{\left(r_{c,j}, a_j, E_j\right) : r_{c,j} \in \Delta(\mathbb{S}_i), a_j = a_i + 1, E_j = E_i \times \left(r_{c,i}/r_{c,j} + 1\right)/2\right\}$. Furthermore, a heat treatment permits the transition from state $\mathbb{S}_i = (r_{c,i}, a_i, E_i)$ where $a_i \geq 1$ to state $(r_{c,i}, 0, 1.0)$. Accordingly, we define the set of all preceding states from which state $\mathbb{S}_i$ can be reached as $\mathcal{P}(\mathbb{S}_i) = \left\{\mathbb{S}_j : \mathbb{S}_i \in \mathcal{F}\left(\mathbb{S}_j\right) \text{ and } a_i \geq 1\right\} \cup \left\{\left(r_{c,j}, a_j\right) : r_{c,j} = r_{c,i} \text{ and } a_i = 0\right\}$.

Let $\mathcal{N}_{ij}$ denote the minimum number of drawing stages needed to move from state $\mathbb{S}_i$ to state $\mathbb{S}_j$, and $\mathcal{H}_{ij}$ denote the minimum number of heat treatments. An integrated objective is expressed as $\mathcal{O}_{ij} = f(\mathcal{N}_{ij}, \mathcal{H}_{ij})$, where the function f can take the form of a weighted summation of both objectives. In the trivial case when $r_{c,p} \in \Delta(\mathbb{S}_0)$, the problem can be solved in just one drawing step. Otherwise, the following functional equation is used to evaluate the minimum number of drawing stages and heat treatments combination:

$$\mathcal{O}_{0j} = \min_{\mathbb{S}_i \in \mathcal{P}\left(\mathbb{S}_j\right)} \left\{\mathcal{O}_{0i} + \mathcal{O}_{ij}\right\} \tag{19}$$

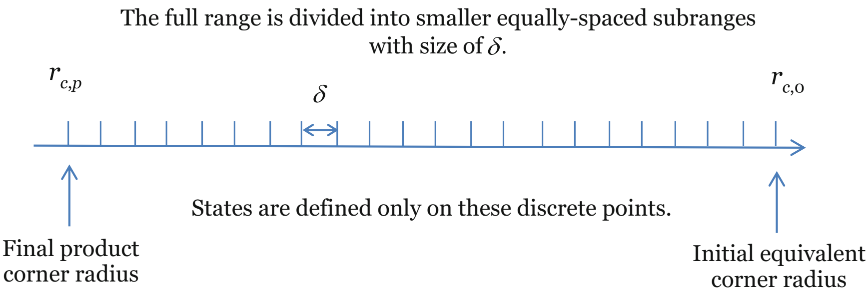


Fig. 9 Discretizing the search space

Since the box corner radius is a continuous variable, there is infinite number of states in the search space. Fortunately, it is not necessary to investigate all states in the search space since constraints (5) and (6) define discrete values for the corner radius beyond which no feasible states can be reached. Therefore, it is sufficient to discretize the search space by dividing the range from $r_{c,0}$ to $r_{c,p}$ into smaller sub-ranges. For simplification, these sub-ranges are selected to be equally sized with a size denoted δ as shown in Fig. 9. Accordingly, it is required only to evaluate the values of $\mathcal{O}_{0j}$ at corner radii that equal $r_{c,0}+\delta$, $r_{c,0}+2\delta$, $r_{c,0}+3\delta$, and so on.

The selection of the sub-range size δ is crucial for the success of the application of dynamic programming to the studied problem. If it is selected to be too wide, the optimal solution might be missed and the obtained solution will be suboptimal. If it is selected to be very narrow, unnecessary extra computational time and memory will be needed without really improving the quality of the optimal solution obtained. As a general guideline, it was found that a sub-range size that will result in 300 sub-ranges represents a sufficiently small size for finding optimal solutions with an acceptable computational time and memory requirements. On the other hand, the larger the sub-range size is, the lower the number of process plans will be, leaving the decision maker with few alternatives to select from. Therefore, the application of the proposed technique requires some preliminary investigations by the decision maker through trying experimental values of sub-range sizes until a sufficient number of optimal process plans are generated.

By solving the recursive Eq. (19), all feasible, optimal paths from state $\mathbb{S}_0$ to any of the terminal states in set $\mathbb{T}$ can be easily determined. Each of these paths defines a process plan in which the post-drawing box corner radius after each stage along with the requirement of conducting heat treatment is defined while having the minimum objective value.

The output of the dynamic programming approach is given in the form of a set of feasible process plans that have the same minimum objective value. A validation of the applicability of the elected process plans is conducted through a finite element analysis.

6.2 Finite Element Modeling and Analysis

The finite element method has been used for decades to study different aspects of sheet metal forming. The success or failure of a certain sheet metal forming process depends on many parameters and can be predicted easily using the finite element method. In addition, the outcome of different process design techniques can be verified using the finite element method and if needed can be altered or adjusted to obtain a successful process. This section presents an overview of the finite element modeling of multistage deep drawing processes with emphasis on box shapes. It is not intended to cover the theory underlying the finite element method. It discusses some crucial tricks and pitfalls of unexperienced finite element users that may lead to inaccurate results as observed in some recent publications.

While the quasi-static implicit finite element solver can be used to model sheet metal forming, difficulties with convergence and large number of iterations required had given the dynamic explicit solver the advantage. In such dynamic explicit solver, the equations of motion for the body are integrated using the explicit central-difference integration rule. The default time incrimination scheme in many commercial softwares, such as ABAQUS/Explicit which is adopted here, is fully automatic and requires no user intervention. It allows for solving high nonlinear problems involving both material and geometrical nonlinearities along with sophisticated contacts.

Figure 10 shows one of the basic steps used to build a finite element model for sheet metal forming in accordance with the common procedure used in ABAQUS®/CAE (ABAQUS 2014). The process starts by developing the three-dimensional parts of the blank, punches, and dies. The blank is modeled as a deformable body using shell part, while the punches and dies for multistage drawing process are simulated using rigid bodies (shells). Two methods can be used to define rigid parts: Analytical or Discrete definitions. Analytical rigid parts are used for simple geometries that can be defined using revolutions of simple lines and arcs and hence require no mesh definitions. The discrete part definition is used for more general geometries and part has to be meshed to define the part's surfaces. Furthermore, the kinematics of the rigid part is defined at a reference point attached to the part. All displacements, velocities, and forces applied to the rigid part are defined at the reference point. If the motion of the rigid part is not constrained in any direction, both point mass and rotary inertia are to be defined at the reference point.

For deep drawing simulations, all degrees of freedom of the reference point are to be constrained except in the punch travel direction. The second step in this process is to define the properties of the model. These include materials, sections, mass and inertia, and material's orientation and being defined under the property module. Small mass is assigned to the reference point of rigid parts to minimize inertia effects and is essential for dynamic analysis. Under the material definition, the minimum input required to run the analysis includes material's density, Young's modulus, Poisson's ratio, and the yield stress and the corresponding plastic strain flow curve. A representative example of the yield stress and the corresponding

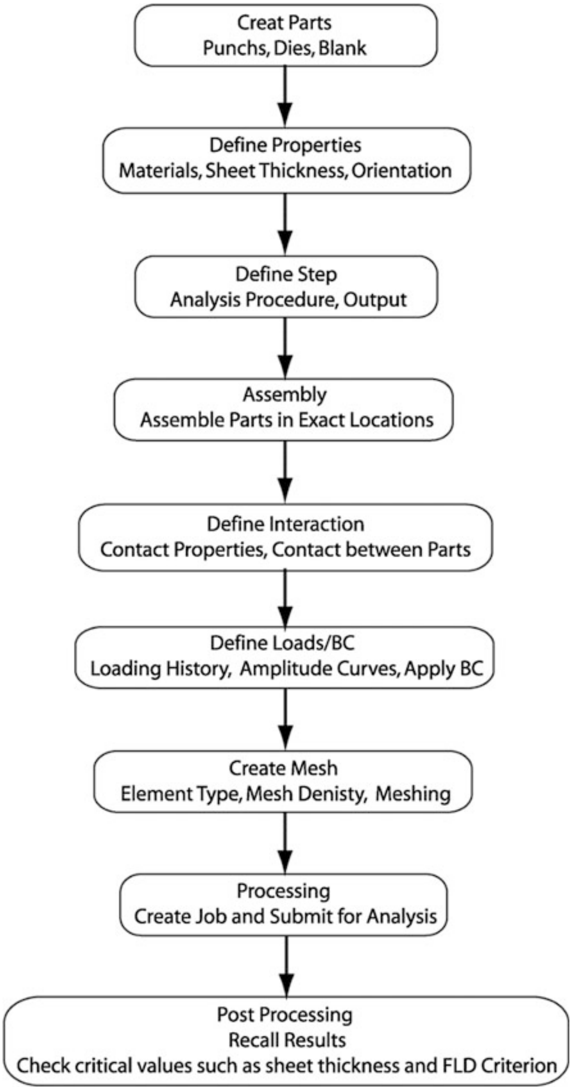


Fig. 10 Necessary steps required to build the finite element model

plastic strain flow curve is shown in Fig. 11. Here, the material has a linear hardening profile. It should be noted that under deformation conditions where the plastic strain exceeds the maximum plastic strain in the input data ($\varepsilon_{\text{peak}}$ in Fig. 11), the corresponding yield stress will remain constant at the peak value of the input data (σ_{peak} in Fig. 11). Consistent units must be used to obtain valid analysis as instructed in the user manual of the finite element package.

The use of finite element also allows for modeling different aspects of sheet metal forming such as material's anisotropy, rate dependence, and failure criteria. With respect to the latter, for example, localized necking cannot be modeled with

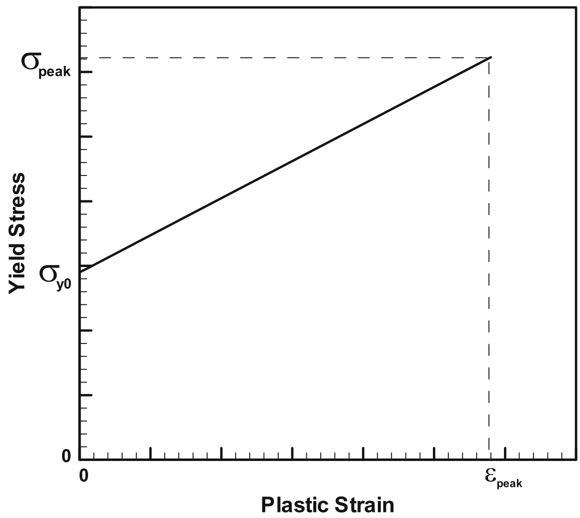


Fig. 11 Yield stress and plastic strain for a linear harding material

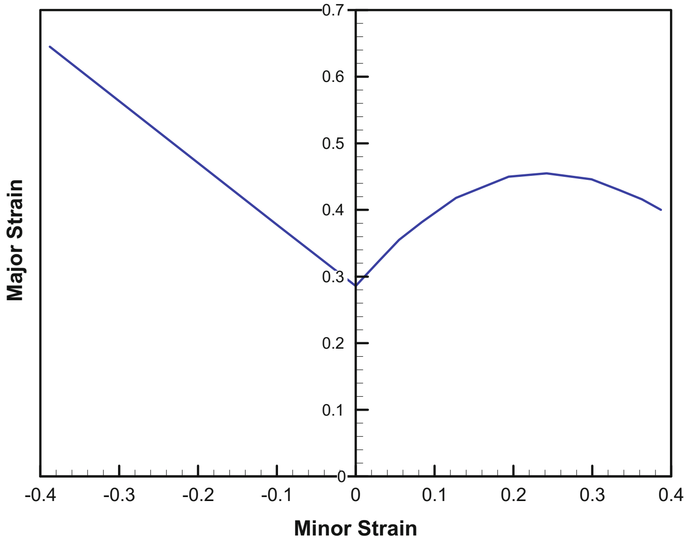


Fig. 12 Illustration of FLD data used to predict failure in sheet metal forming

traditional shell elements used in sheet metal forming simulations because the size of the neck is of the order of the thickness of the element. Instead, forming limit diagrams (FLD) (Keeler and Backofen 1964; Goodwin 1968) are used to predict the material's failure during the drawing process. An example of the FLD is illustrated in Fig. 12. Classical strain-based forming limit diagrams (FLDs) are known to be

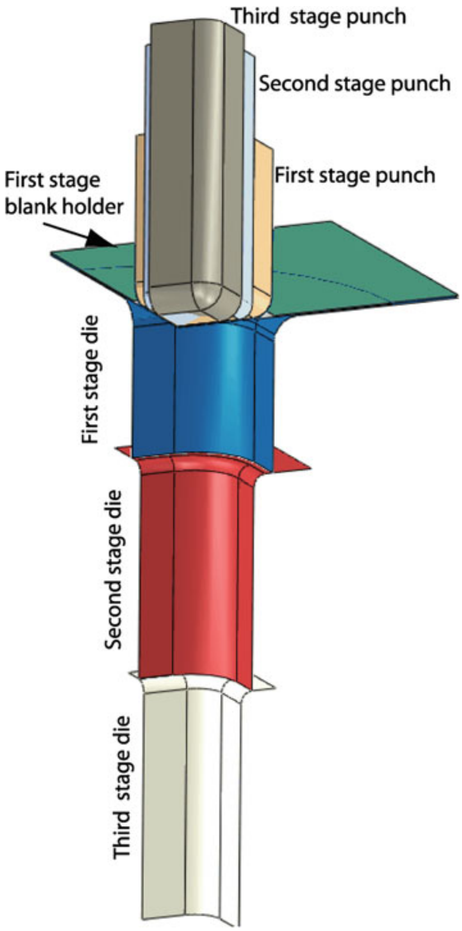


Fig. 13 Multistage drawing model

dependent on the strain path. Changes in the deformation mode (e.g., equibiaxial loading followed by uniaxial tensile strain) may result in major modifications in the level of the limit strains. In practical industrial applications, significant changes in the strain path may be induced by multistep forming operations, complex geometry of the tooling, and interface friction, among other factors.

Under the assembly module, the multistage drawing process is simulated in one job where all the dies are built in tandem, i.e., one after the other as shown in Fig. 13 for a square box example. Due to the double symmetry, only one-quarter of the model is considered. It should be noted that symmetry assumptions are utilized in the present analysis. However, in problems where wrinkling, earring, and other anisotropic material behavior are of interest, a full 3-D model is used. The punches are built at the same location where no contact interaction is defined among them. In the first stage of the drawing process, all the punches travel together where the only active contact is between the punch of the first stage and the blank. In subsequent drawings, the punch of the first stage acts as a blank holder for the second stage, the contact is activated between the punch of the second stage and the blank, and so on.

The following step is to define the analysis procedure. Two approaches can be used in modeling the deep drawing process, General Static or Dynamics Explicit procedures. The general static procedure requires small number of increment, however, large number of iterations per time increment. Moreover, the system of equations of the whole system is solved iteratively. In addition, in case complex contact and the existence of friction, the rate of convergence will be slow and difficult to achieve equilibrium in many cases. In contrast, the dynamic explicit solver uses small time increment; however, the computational cost per increment is inexpensive as compared to the static analysis because it is not required to solve a set of simultaneous equations as in static implicit analysis. The stable time increment during analysis is determined as

$$\Delta t = \frac{l}{c} \tag{20}$$

where l is the minimum element length in the model and c is the wave speed of the material and is defined as $c = \sqrt{E/\rho}$ where E is the Young's modulus and ρ is the mass density. For example, for an element with minimum side length of 1 mm for a finite element model using steel, the stable time increment is approximately 2×10^{-7} s. A mass scaling technique can be used to artificially increase the mass density and hence increase the stable time increment. A mass scaling factor of 25 will increase the stable time increment by 5 times. However, this mass scaling factor will enhance the inertia effects and has to be used with cautions. It should be noted that dynamic explicit solver is intended to be used in dynamic events where the simulation time is on the order of few micro seconds. Larger time events will take large number of time increments and longer solution times. To expedite the solution process, the simulation is conducted at an artificially high speed compared to the physical process. However, if the speed increased substantially, the solution will not correspond to the low-speed physical process and inertia effects will dominate the analysis. In a typical deep drawing process, the punch travel may be as high as 1 m/s which is approximately 0.5 % of the wave speed for steel and aluminum. In general, inertia effects will not play a dominant role for forming rates that are considerably higher than the nominal 1 m/s rates found in the physical problem. Unlike static implicit solver, explicit solver uses a finite-strain, large displacement, large-rotation formulation by default. Since solution efficiency is usually an important factor when using explicit solvers, only first-order reduced-integration elements are generally available. Under the step definitions, an annealing step can be simulated at any stage to retrieve the original state of the material.

The contact property and contact definitions are defined under the interaction module. The contact property defines the type of normal and tangential behavior of contacting surfaces. Under the tangential behavior, different friction conditions such as frictionless, penalty, and rough conditions can defined. The friction coefficient between contacting surface can be assumed based on the reported experimentally measured friction coefficient for deep drawing processes which are found to vary between 0.015 and 0.45 (Jurkovic et al. 2006). Higher friction coefficients are not usually desirable in simulations as they may lead to sticking conditions and convergence difficulties. The general contact algorithm under the explicit solver offers great flexibility in contact definitions but lead to higher computational cost. Surface-to-surface contact definition can be used if the definition of the contact can be predicted and does not change during the analysis. Turning contact definition On and Off allows to activate and deactivate the contact interaction as needed.

As stated above, the load and boundary conditions for rigid parts are defined at the reference point. For all dies, all degrees of freedom are constrained while for all punches all degrees of freedom are constrained except in the travel direction. The blank holder pressure is applied as an equivalent concentrated force at the reference node. The punch travel is defined as a prescribed displacement at the reference point during the forming step. An amplitude curve is used to define the rate of displacement prescribed at the reference point. To minimize the inertia effects, a smooth amplitude curve is used. The smooth amplitude definition creates a fifth-order polynomial transition between two amplitude values such that the first and second time derivatives are zero at the beginning and the end of the transition. When the displacement time history is defined using the smooth curve definition, the velocity and the acceleration will be zero at every amplitude value specified as shown in Fig. 14.

The blank in sheet metal forming is commonly modeled with shell elements adopted by Belytschko et al. (1984). Unlike the three-dimensional continuum elements which are computationally expensive, shell elements are the best choice when it comes to modeling deep drawing processes that do not involve ironing processes and they provide the true thickness distribution directly. Shell element family comes in a variety of options including thin and thick shell, linear and quadratic, hour glass control, and reduced and full integrations. The meshing quality has significant impact of the results specially when using dynamic explicit solver. Different approaches are available to mesh parts. Table 2 shows the mesh

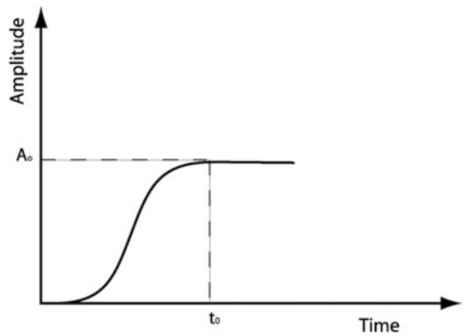
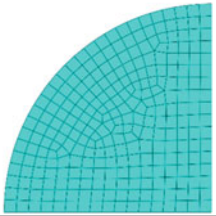
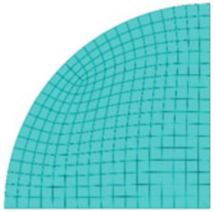
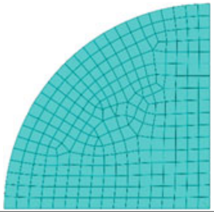
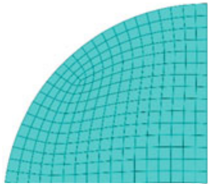
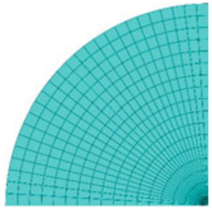
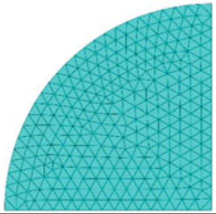
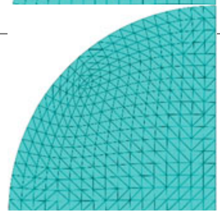


Fig. 14 Smooth step amplitude curve

Table 2 Meshing of a quarter of a circular blank using different mesh controls

		Technique		
		Free	Structured	Sweep
Element type	Quadrilateral			Not available for this geometry
	Quadrilateral dominated			
	Triangular			Not available for this geometry

generated using different mesh controls. The goal is to obtain uniform and symmetric meshes to obtain reliable results. Using partitions may help to produce more uniform meshes. Mesh size to be used must be smaller than any geometric feature in the finite element model. A mesh size sensitivity analysis must be conducted prior to any simulation to eliminate the errors related to the element size. Furthermore, biased seeding can be used in areas of large deformations or of interest to the simulation process.

7 Case Studies

Box-shaped parts that are very deep or with large aspect ratio are known to be difficult to be produced by deep drawing due to severe deformation patterns. To demonstrate the effectiveness of the developed integrated AI approach, two case studies for a very deep square and a rectangular box with large aspect ratio are presented. The two box-shaped cases were originally introduced by Sachs (1966) and Waller (1978), and for which additional rule-based (RB) process plans were presented by Wifi et al. (2010). Part of the developed integrated AI approach was applied earlier in Abdelmaguid et al. (2012) and included in this work with additional explanation and discussion on the results.

In both cases, the part material is stainless steel 304 sheet with a thickness of 1 mm. The yield strength, the ultimate tensile strength, strength coefficient, and the strain hardening exponent are 295, 621, 1275, and 0.45 MPa, respectively. The material is assumed to be isotropic and homogeneous, and the heat generated by plastic deformation is neglected because of the limited speed used in the process. The main material properties that are needed for applying dynamic programming are given as $E_{max} = 1.9$, $m_0 = 0.5$, and $m_1 = 0.8$. The FLD data used is those produced by Tourki et al. (2005). The friction coefficient between contacting surfaces is assumed equal to 0.15 based on the reported experimentally measured friction coefficient for deep drawing processes which were found to vary between 0.015 and 0.45 (Jurkovic et al. 2006).

In the studied cases, different preliminary dynamic programming trials with step sizes δ of 5, 2, 1, and 0.5 mm are conducted. The number of drawing stages is found to be minimum at step sizes of 1 and 0.5 mm. The number of alternative plans at each level is found to be increasing with the decrease of δ, which is reasonable since the decrease of δ allows for more corner radii to be evaluated.

7.1 Square Box

In this case study, a square part with dimension 58 × 58 × 100 mm is considered. The results obtained by RB process planning approach (Wifi et al. 2005, 2008) are compared to the results of the proposed dynamic programming technique. There is only one process plan generated by the RB system which was tested via finite element simulation by Wifi et al. (2010). The RB plan, shown in Table 3, consists of three drawing stages and one heat treatment after the second stage. The maximum FLD damage factor and minimum sheet thickness distributions after the first stage were 0.66 and 0.75 mm, respectively. However, the second stage did not complete due to strain localization. To reset the material ductility, an anneal step after the first stage was suggested in contradiction of the RB plan to be able to continue drawing the process. The resulting maximum FLD damage factor and minimum sheet thickness after the third stage were 0.81 and 0.63 mm, respectively.

Unlike the classical RB approach, dynamic programming suggested 11 alternative distinct process plans at a step size of 1 mm, which could be further tested using the finite element simulation. However, since the finite element simulation is time consuming, not all the 11 different plans are tested. Only two dynamic programming plans are selected, namely DP Plan 1 and DP Plan 2 as shown in Table 3. These two plans have the least strain severity factor *E*. The results for DP Plans 1 and 2 after each drawing stage are given in Figs. 15 and 16, respectively. As can be seen from these figures, the drawing process continued to the final stage

Table 3 RB and selected DP plans for the square box example

Plans	Stage #	$r_{c,i\text{-}1}$	$r_{c,i}$	$r_{c,i}/r_{c,i\text{-}1}$	E	$l_{p,i}$ (=$w_{p,i}$)	$h_{p,i}$
RB Plan	1	44.72	23.7	0.53	1.443	84.58	65.04
	2	23.7	18.96	0.8	1.624	67.67	90.43
	Heat treatment						
	3	18.96	10.00	0.527	1.448	58.00	100.00
DP Plan 1	1	44.72	23.72	0.5304	1.443	92.32	51.79
	2	23.72	19.72	0.831	1.589	80.88	65.12
	Heat treatment						
	3	19.72	10.00	0.507	1.486	58.00	100.00
DP Plan 2	1	44.72	22.72	0.508	1.484	88.43	56.07
	2	22.72	18.72	0.824	1.643	78.29	68.52
	Heat treatment						
	3	18.72	10.00	0.534	1.436	58.00	100.00

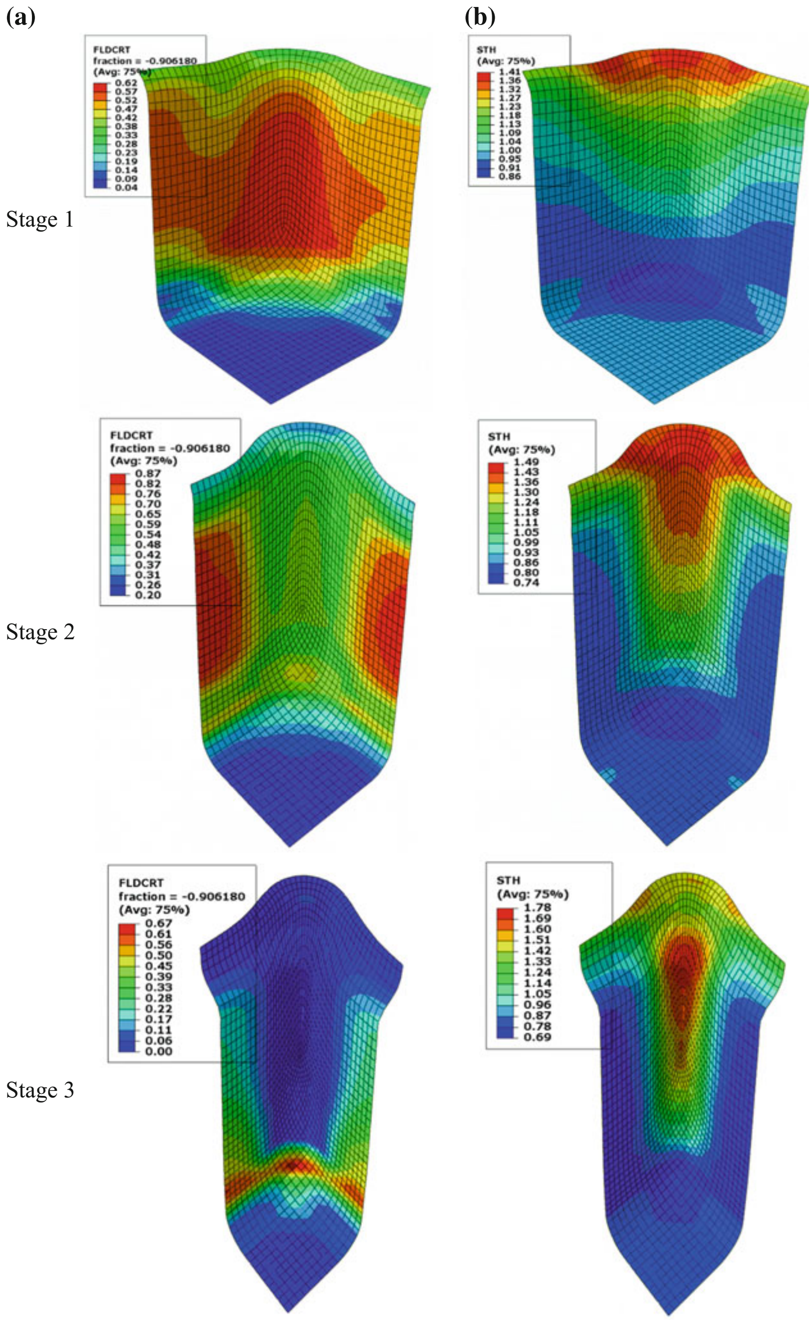


Fig. 15 Square box for DP Plan 1 **a** FLD damage factor; **b** sheet thickness distribution after each drawing stage

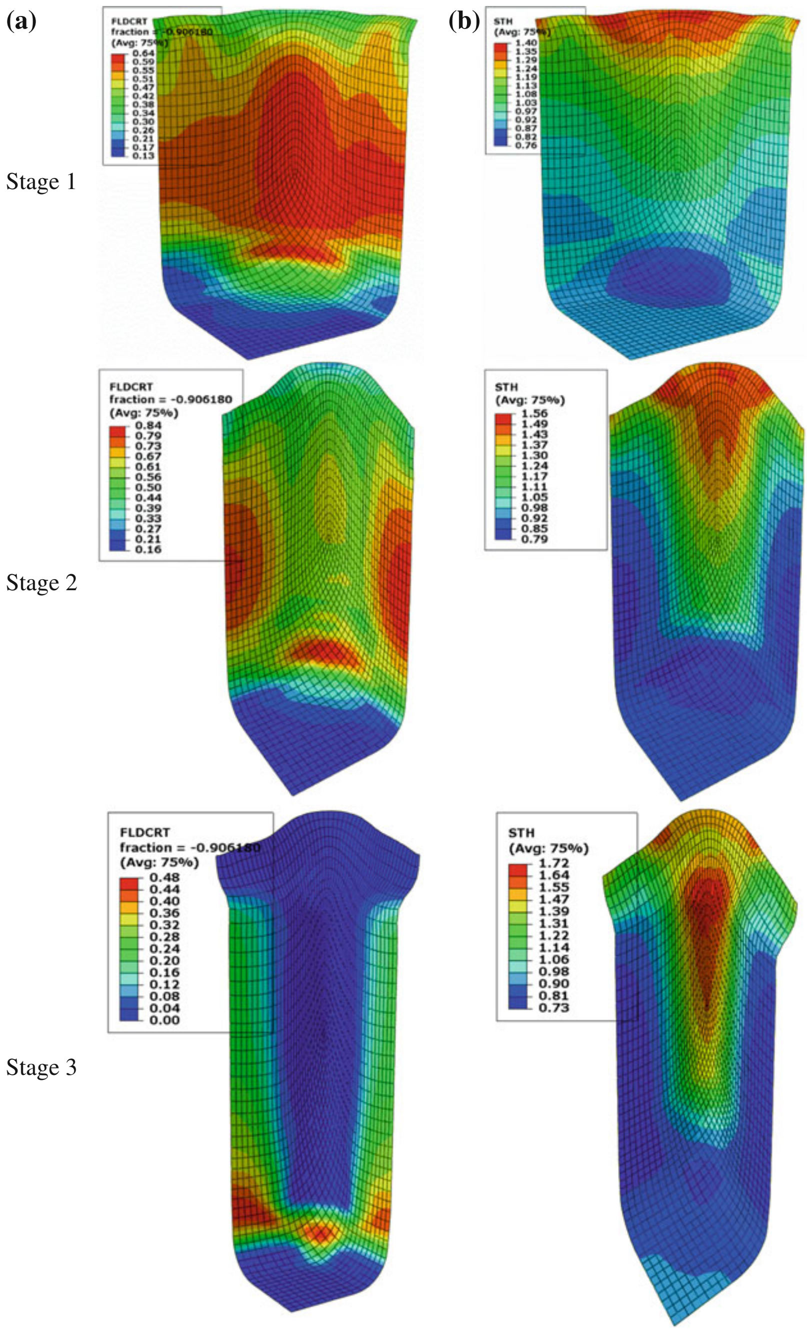


Fig. 16 Square box for DP Plan 2 **a** FLD damage factor; **b** sheet thickness distribution after the third stage

with no interference or refinement to the simulation process. Moreover, both Plans 1 and 2 yielded reasonable FLD damage factor of 0.67–0.48 and final sheet thickness 0.69–0.74 mm for Plans 1 and 2, respectively.

It should be noted that the deformation pattern is more severe at the corner region and symmetric around it. This is clearly shown in the mesh distortion at the corner zone as indicated in Fig. 17 where straight lines in mesh tend to skew away in the corner zone. This is also shown by the plastic strain distribution in the box wall in Figs. 18 and 19 for Plans 1 and 2, respectively, where the plastic strains

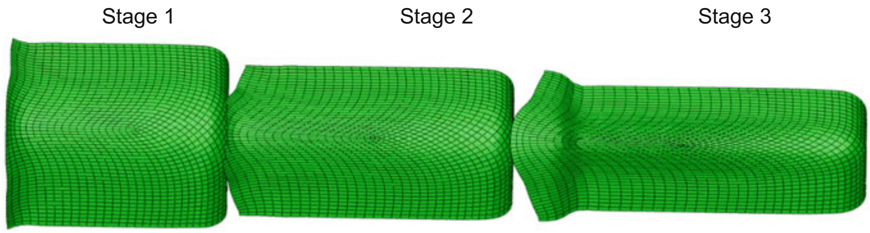


Fig. 17 Deformation pattern in *square box* example

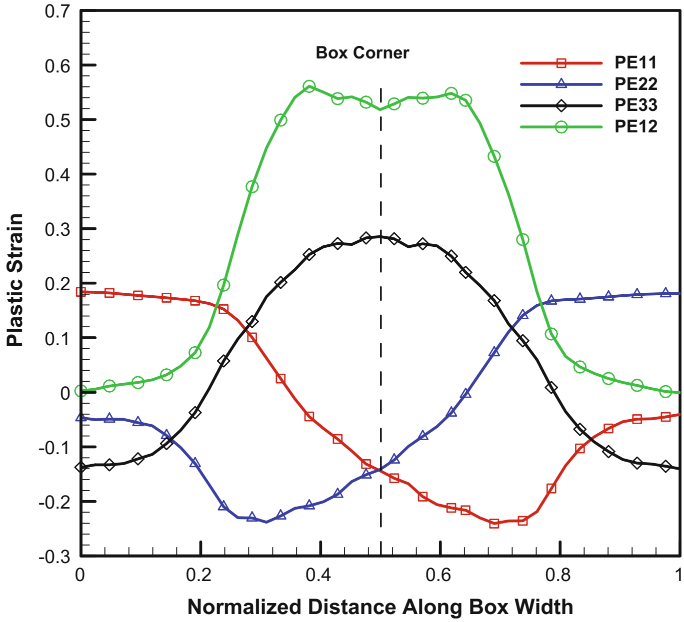


Fig. 18 Plastic strain distribution in *square box* example of DP Plan 1

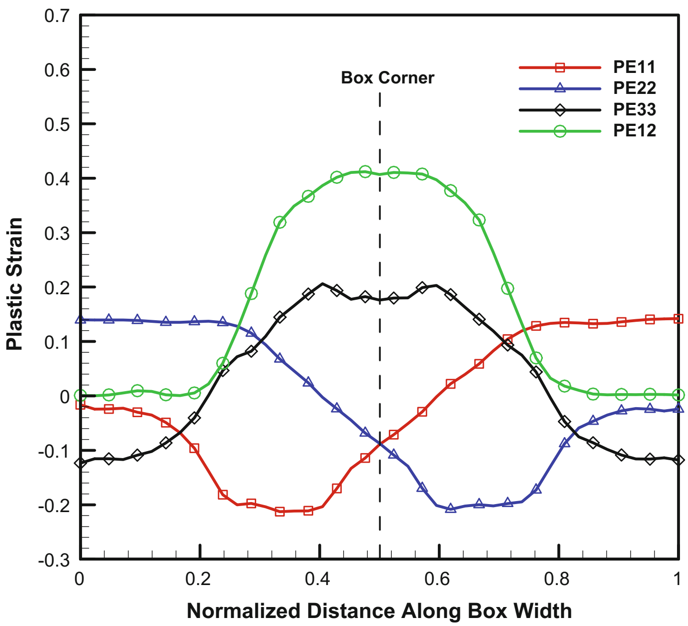


Fig. 19 Plastic strain distribution in *square box* example of DP Plan 2

(PE11, PE22, PE33, and PE12) are high at the corner zone and symmetric around it. It is clear from these two figures that the strain severity in Plan 2 is less than Plan 1 as indicated by the maximum in plan plastic shear strain PE12 and through thickness strain PE33.

7.2 Rectangular Box with Extreme Aspect Ratio

In this case study, a rectangular flangeless part, with dimension 342 × 100 164 mm, is considered. Analysis using classical RB was discussed by Wifi et al. (2010). The RB plan did not pass the finite element test and Wifi et al. (2010) had to modify the RB input parameters such as the die profile radius to achieve a successful process. For the DP implementation in this case study, a step size of 0.5 mm is selected which allowed for generating 10 alternative distinct plans with the same number of three drawing stages and one heat treatment. Three optimized plans with the lowest values of E are selected and shown in Table 4. These plans are tested via

Table 4 Selected DP plans for the rectangular box with extreme aspect ratio example

Plans	Stage #	$r_{c,i\text{-}1}$	$r_{c,i}$	$r_{c,i}/r_{c,i\text{-}1}$	E	$l_{p,i}$	$w_{p,i}$	$h_{p,i}$
Plan 1	1	107.00	54.00	0.505	1.491	421.88	123.36	126.32
	2	54.00	38.00	0.704	1.805	395.25	115.57	137.36
	Heat treatment							
	3	38.00	20.00	0.526	1.450	342.00	100.00	164.00
Plan 2	1	107.00	53.50	0.500	1.500	417.97	122.21	128.40
	Heat treatment							
	2	53.50	28.50	0.533	1.439	392.65	114.81	138.31
	3	28.50	20.00	0.702	1.744	342.00	100.00	164.00
Plan 3	1	107.00	57.00	0.533	1.439	445.32	130.21	114.45
	2	57.00	40.00	0.702	1.744	410.88	120.14	128.79
	Heat treatment							
	3	40.00	20.00	0.500	1.500	342.00	100.00	164.00

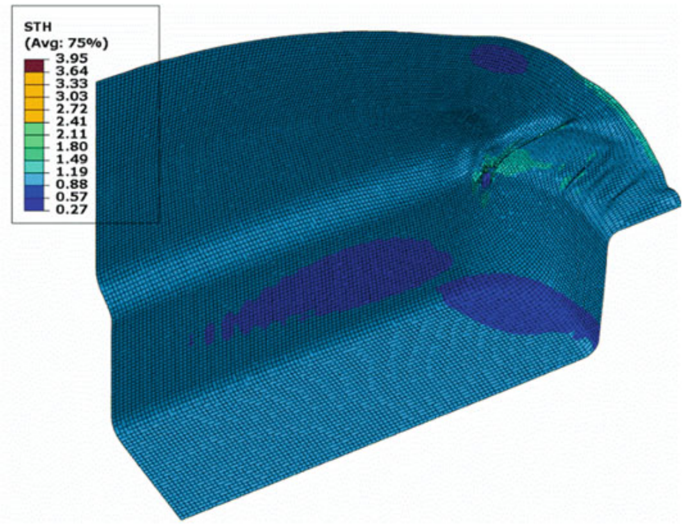


Fig. 20 Rectangular box sheet thickness distribution during stage 2 in Plan 1

finite element simulation to determine their performance in producing the required part. Plan 1 did not succeed due to wrinkling and thinning during stage 2 as shown in Fig. 20. Both Plans 2 and 3 pass the finite element test and the analyses completed to the end of the third stage safely. Figure 21 shows the produced parts using these plans as well as the sheet thickness distributions at the end of the third stage.

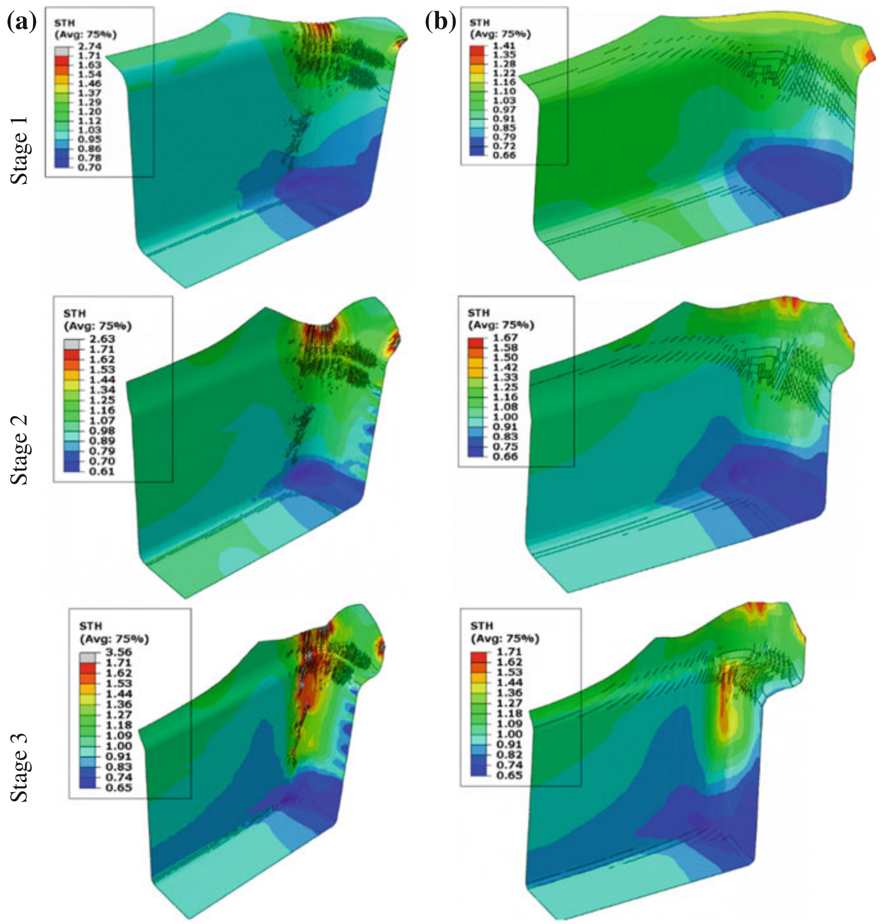


Fig. 21 Rectangular box sheet thickness distribution after each stage: **a** Plan 2; **b** Plan 3

However, the analysis showed that Plan 3 resulted in more uniformity in sheet thickness and less tendency to wrinkling as compared to Plan 2. Plan 3 is thus considered the optimized process plan for this case.

It should be noted here that the governing rules used by dynamic programming assume constant thickness during the analysis. This is obviously not true as the sheet thickness varies along the box wall. The deformation in the case of rectangular box with large aspect ratio is more severe as compared to the square box case and is

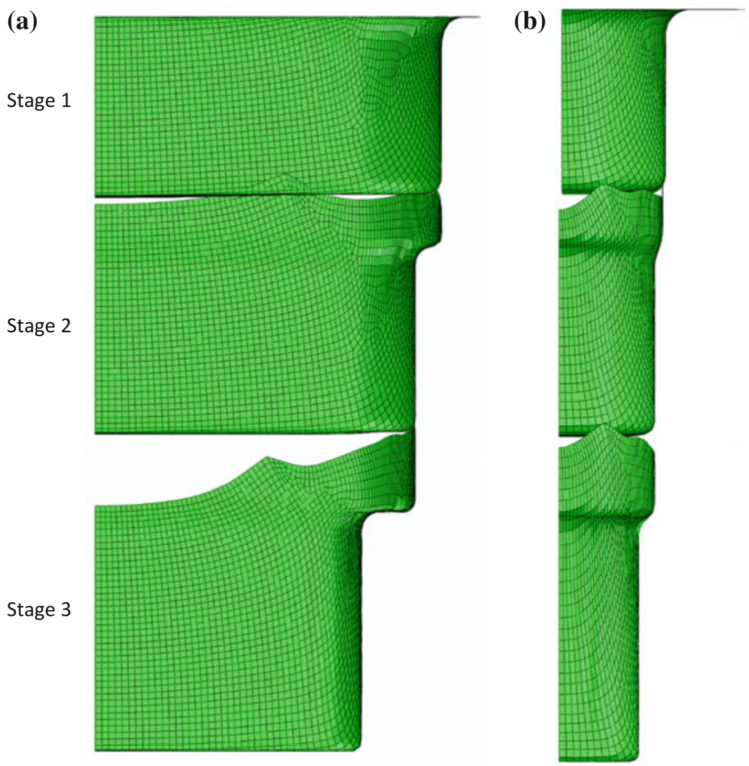


Fig. 22 Deformation pattern in the *rectangular box* wall **a** length wise, and **b** width wise

unsymmetrical around the corner. Figure 22 shows the deformation pattern length and width wise where the mesh distortion is higher in width direction. Figure 23 shows the variation of the sheet thickness along the corners at the bottom of the rectangular box where the change in the wall thickness (thinning) is quite high in the width direction. Plan 3 shows relatively slight better thickness reduction as compared to Plan 2. Moreover, the plastic strain distributions for the two plans show no difference where, as in the square box example, the plastic shear strain attains its maximum value around the corner of the box as shown in Figs. 24 and 25.

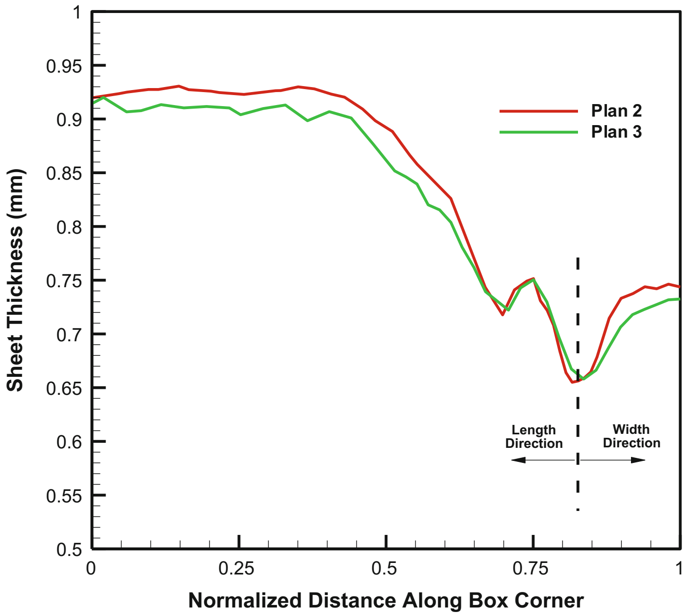


Fig. 23 Sheet thickness distribution along the corners at the *bottom* of the *rectangular box* at the final stage for plans 2 and 3

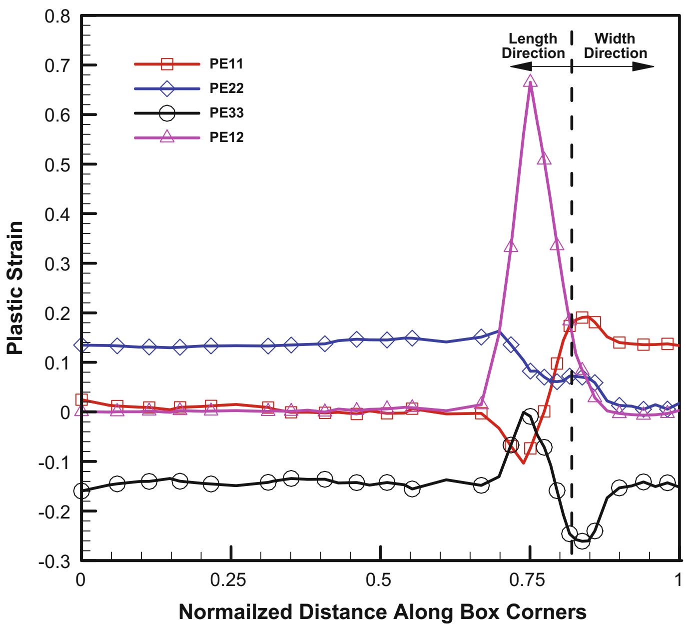


Fig. 24 Plastic strain distribution in *rectangular box* example of Plan 2

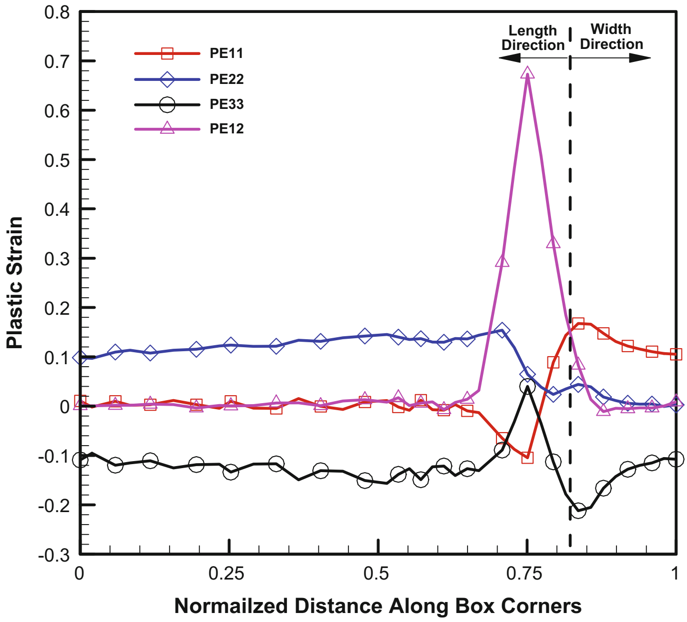


Fig. 25 Plastic strain distribution in *rectangular box* example of Plan 3

8 Concluding Remarks

The main concern of the deep drawing industry is to optimize the process parameters and process plans in order to get a complete deep drawn product with least defects and high limiting drawing ratio (LDR). This optimization of the deep drawing process is necessary to improve important industrial performance measures such as productivity and cost of goods manufactured. The present work provides a systematic approach for determining optimized process design plans with the minimum possible number of stages and heat treatments to be set to achieve the objectives of maximizing product quality and minimizing costs.

In this article, an integrated AI approach is suggested to generate a set of alternative optimized process plans for deep drawing of box shapes. The developed constraints in this approach are based on traditional widely accepted process design rules. The validation of the process parameters for the multistage deep drawing of box-shaped parts have been investigated using the finite element method with full account of formability limits.

The study demonstrates that the integration of the rule-based (RB) computer-aided process planning (CAPP) with the dynamic programming (DP) optimization and finite element (FE) validation could be a valuable, reliable, and a more rational AI approach to this complicated problem. The process plan generated by DP is the initial stage before applying FE. As detailed in the article, wider ranges of process parameters are scanned collectively in this DP module with the target of minimizing the number of stages and reach least overall strain severity.

However, within the limited amount of examples considered, it is rather difficult to make a general conclusion a priori as of which plan is capable of producing a smooth and safe process with more thickness uniformity as obtained by the finite element analysis constraints that are defined by the limiting drawing ratio and strain severity limits. Feasible process plans describe process plans that are suggested either by the RB or DP method and satisfy the parameter constraints of the process design rules. These feasible process plans are then tested using FE simulation to verify its applicability. However, the flexibility given by the DP approach lends itself as a rational approach for giving more choices of plans to elect among them the optimized plan giving least severity and maximum uniform thickness distribution in the FE analysis (Abdelmaguid et al. 2012).

No claim is made here that the presented work is complete. The complexity of the problem calls for further studies taking the peculiarities of different materials, formability limits and the complexity of part geometry. Indeed, there is growing interest in the research community to apply different optimization approaches to the deep drawing process to provide a systematic method for determining the process parameters (Wifi and Abdelmaguid 2012). Various lines of optimization research are of interest and are worth considering for future implementation into the suggested AI-integrated approach. This includes for instance the optimization of the blank holder force to avoid wrinkling and fracture, the development of optimum blank shapes, and optimizing deep drawing process parameters to help in reducing the energy consumed and in avoiding fracture.

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Knowledge-Based System for Design of Deep Drawing Die for Elliptical Shape Parts

D.H. Park

1 Introduction

In general, deep drawing products have various cross-section shapes such as cylindrical, rectangular, and non-axisymmetric shapes. Much research for cylindrical products has been carried out as the fundamentals of the deep drawing process (Park 1997; Kim 2001). The knowledge-based system for the deep drawing process reported in previous publications are mostly definite for axisymmetric products (Choi et al. 2001; Park et al. 1999a, b, c), and studies for non-axisymmetric products have not been published yet (Kang et al. 2001; Park et al. 1999a, b, c, 2000a, b, c, d, e, 2002; Park and Kang 2001; Park and Yarlagadda Prasad 2004, 2005; Choi et al. 1999a, b). Therefore, it is vital to apply the knowledge-based system to the non-axisymmetric products. This study presents an overview of the process sequence design and construction of the knowledge-based system to apply to the non-axisymmetric product with elliptical shape. In this study, the cross-section of the product body consisting of a round in the major axis and a straight line in the minor one is defined as elliptical.

Among the methods used to form sheet metal, deep drawing is mainly used to produce vessels, vehicle parts and housings. Deep drawing products, generally, have many cross-section shapes (Kim 1999). There are rotationally symmetric products, which are cylindrical, square, rectangular, and other non-axisymmetric shapes. Many studies concerning cylindrical products have been performed in order to determine the fundamentals of deep drawing process. So, this has made many applied shapes such as rectangular, elliptical, and non-axisymmetric shapes. (Kawai et al. 1987; Kim and Kobayashi 1986; Bae et al. 1998) In general, most of the studies on deep drawing process have been addressed the formability of axisym-

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metric shapes, but there have been few studies done on the formability of non-axisymmetric shapes.

Deep drawing is a complicated process, and it is not possible to determine the actual press working properties of a particular metal by a single test method (Yang and Nezu 1999; Walczyk and Hardt 1999; Lo and Jeng 1999). The chief methods currently used are the Erichsen test, the Conical Cup test, and the Scribed Circle test. Because steel sheets are manufactured by rolling, the crystalline structure is fibrous in an appearance, and the mechanical properties of the sheets are direction dependent. This tendency is more pronounced in cold-rolled sheets than in hot-rolled sheets. In general, resistance to deformation is high in the rolling direction, but it is minimal at a declination of 45° to the rolling direction. Elongation is maximum in the rolling direction and minimum in the direction perpendicular to it. This is why four ears are formed during deep drawing. To ensure optimum results in press working, it is important to take note of the material grain direction when feeding it into the press.

Recently, many researches on knowledge-based systems used in sheet metal forming have been reported. Park et al. (2000a, b, c, d, e), Park and Kang (2001) constructed an automated knowledge-based system for axisymmetric deep drawing products. Eshel et al. (1986) developed the Automatic Generation of Forming Process Outlines (AGFPO) system for axisymmetric and monotonic parts, produced by deep drawing. They suggested a Generation and Test, Rectification (G&TR) strategy for the process planning of axisymmetric deep drawing products. The system relies on experience-based die-design guidelines for its process sequence design. Sitaraman et al. (1991) developed a knowledge-based system in axisymmetric sheet metal. Tisza (1995) presented a group technology and modularity in an expert system (Chang 1990; Oh 1998; Joe 1997; Park 1998; Badiru 1992). Jin (1989) constructed a computer-aided process planning system for cylindrical and rectangular products. Perrotti et al. (1985) developed a program, which calculates the dimensions of the blank of subsequent forms of a steel sheet to obtain a piece with final rectangular plant. A knowledge-based system has been applied to process design as one of expert system. Until now, the constructed knowledge-based systems for deep drawing processes have mostly been applications for axisymmetric products, but research on non-axisymmetric products has been rare. Therefore, it is necessary to apply the knowledge-based system to non-axisymmetric elliptical products.

The present study is to construct a computer-aided knowledge-based system for a non-axisymmetric elliptical deep drawing product. The suitability of this system is verified by applying it to an actual deep drawing product. To improve the formability of the non-axisymmetric elliptical deep drawing process, deep drawing tests have been performed on the process variables, such as the punch and die radii, blank shapes and sizes, and punch loads, which are based on the blank shapes. The research has been carried out using diverse technologies. The body shape for a non-axisymmetric elliptical deep drawing product consists of a round in the major axis and a straight line in the minor axis; the system was reflected by using the characteristics of the product shape. By interviewing field engineers, process planning rules are generated and developed on the basis of plasticity theories, handbooks, the know-how of the field engineers, and experimental results. The interviews were recorded, and transcribed, then double-checked with the engineers before the rules formalized.

This study investigates the sequence design process used in a deep drawing process and constructs a computer-aided knowledge-based system for a non-axisymmetric motor frame, which is approximately elliptical in shape (Wagener and Pahl 1991; Im 1999). Owing to the lack of reference data in deep drawing products with non-axisymmetric shapes, acquisition and quantification of industrial practices and empirical data had to be acquired. The resulting process planning rules were based on them, and upgraded by interviewing field engineers. The process planning for a deep drawing product should scientifically account for the shape of the blank, the dimension of the blank, the body shape and the process variables of the product. This study presents a new recognition scheme, a 3-D modeling technique, a modified Entity_List, which was used to create 3-D model, and the accumulated process planning rules, which were used for non-axisymmetric elliptical deep drawing products. Therefore, the system that was developed consists of four modules. The process planning system developed in the study was written in AutoLISP on AutoCAD environment (Kim 1995; Son 2000). The knowledge-based system that was constructed would be very useful in reducing manufacturing lead-time and improving the accuracy of products.

2 Constitutions of the Knowledge-Based System

This system was constructed on the basis of the know-how of industrial field engineers. By interviewing them, the production rules of the surface area calculation and knowledge-based system are generated and developed. The cross-section of the product body, drawing coefficient, punch radius (R_p), and die radius (R_d) considered as the main design parameters. The final product geometry using AutoCAD software, along the major and minor axes of the product is the only input data of the system. The system is composed of shape recognition, 3-D modeling to calculate the surface area, blank design, and process planning modules. Figure 1 shows the flow diagram of the knowledge-based system for non-axisymmetric deep drawing products. The following sections will describe the functions and characteristics of each module.

2.1 Recognition of Shape Module

Because of the difference in the characteristics of product shape, the knowledge-based systems for cylindrical products were not able to recognize non-axisymmetric geometry. Fortunately, it is possible, for elliptical products, to

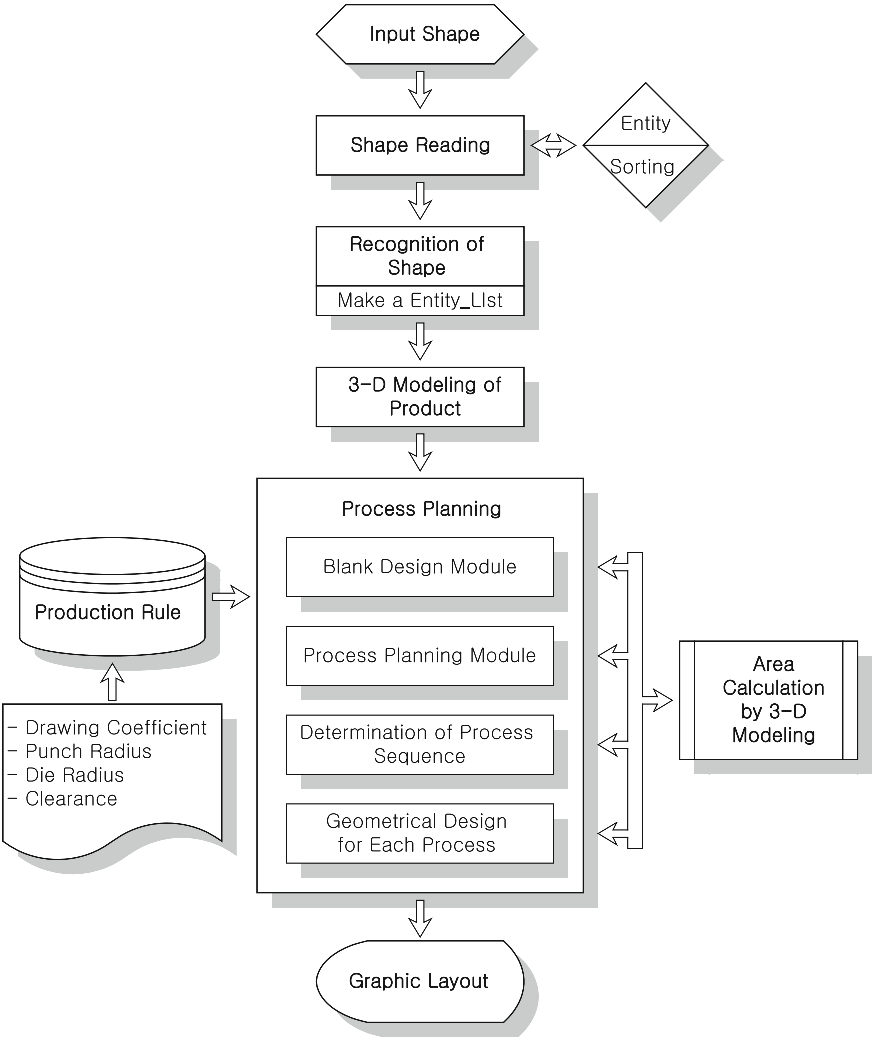


Fig. 1 Flow diagram of the knowledge-based system for non-axisymmetric deep drawing products

recognize the geometry of the product in the major and minor axes by drafting in another two layers on AutoCAD software. From this result, the geometry in each layer can be recognized. It would be a useful method to recognize the geometry for applications to the non-axisymmetric deep drawing products. In this work, the geometry of the major and minor axes in each layer is read, arranged and translated into alphanumeric terms entitled "Entity_List" which consists of seven elements which are name, type, thickness, outer diameter, inner diameter, height, and fillet radius, plus one element including information on reverse drawing.

Entity_List is as follows:

(
(“flange” HL1 T1 OD1 ID1 H1 N1 FR1)
(“wall1” VL1 T2 OD2 ID2 H2 N2 FR2)
(“wall2” TL1 T3 OD3 ID3 H3 N3 FR3)
)

A row shows information on a line and an arc. The first part of the row represents the name of an element: “flange” is the element flange and “bottom” is the element bottom and “walln” (n = 1, 2, 3, …) is the element wall.

The second parts of the rows represent the type of the element: “HL1” is the horizontal list and “VL1” is the vertical list and “TL1” is the taper list. “Tn” is the thickness of the nth element, “ODn” is the outer diameter, “IDn” is the inner diameter, “Hn” is the height, “Nn” is the data with information on the reverse drawing, and “FRn” is the radius of the arc. The structure and contents of Entity_List are shown in Table 1. Figure 2 shows Application of modified Entity_List.

2.2 *Three-Dimensional Modeling Module*

Calculating the surface area of the product is a main procedure for determining the blank dimensions. The surface area of the non-axisymmetric products cannot be calculated as separated components because it is difficult to define the accurate shape of the product. To solve this problem, a 3-D modeling technique was used in this system. This can be applied to a real product by using Entity_List. The total surface areas can be automatically computed by the command “area” in AutoCAD software. Three-dimensional part modeling was used to determine the cup height of the deformation zones in intermediate processes. Figure 3 shows the result of the 3-D modeling for a non-axisymmetric deep drawing product (t = 1.6 mm).

Table 1 Definition of Entity_List

Constitutions	(Entity_name, Entity_type, T, OD, ID, H, N, FR)
Contents	Entity_name: The names of the entity represent
	Entity_type: Class of entity (e.g., HL, VL, TL) (HL: Horizontal, VL: Vertical, TL: Taper List)
	T: Thickness
	OD: Outer Diameter of entity
	ID: Inner Diameter of entity
	H: Height
	N: Null (not used in the system)
	FR: Fillet Radius of entity

```
******* Modified Entity_List in the major axis ******
  (
  ("flange" HL 1.6 70.8 41.8 0.0 0.0 0.5 0.5 0.5 "flange")
  ("wall1" VL 1.6 40.8 40.8 11.3846 0.0 0.5 0.05056 0.21910 "wall1")
  ("wall2" TL 1.6 40.6989 37.0011 3.7926 0.0 0.5 0.05056 0.21910 "wall1")
  ("wall3" VL 1.6 36.9 36.9 43.2846 0.0 0.6 0.6 0.6 "wall1")
  ("wall4" HL 1.6 35.7 25.0 0.0 0.0 0.5 0.5 0.5 "wall2")
  ("wall5" VL 1.6 24.0 24.0 3.0 0.0 2.5 2.5 2.5 "wall3")
  ("wall6" HL 1.6 19.0 13.0 0.0 0.0 0.5 0.5 0.5 "wall4")
  ("wall7" VL 1.6 12.0 12.0 7.6 0.0 0.5 0.5 0.5 "wall5")
  ("bottom" HL 1.6 11.0 0.0 0.0 0.0 0.0 0.0 0.0 "bottom")
  )
```

Fig. 2 Application of modified Entity_List

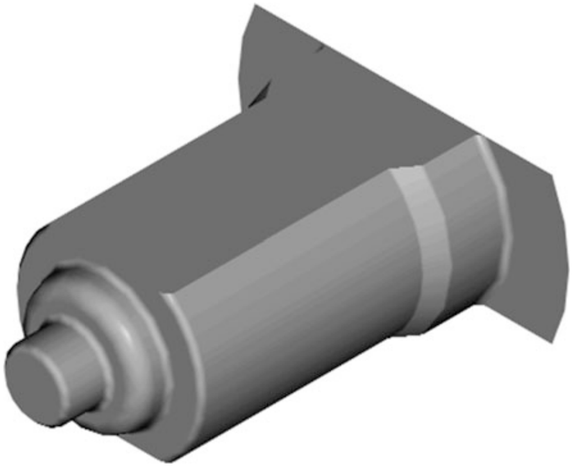


Fig. 3 Three-dimensional modeling of non-axisymmetric deep drawing product (t = 1.6 mm)

As the Entity_List of input geometry was inputted into the 3-D modeling module, a 2-D shape of the product was drafted along the major axis. A line of 0.001 mm in the minor axis was used to minimize effect of thickness in calculating the surface area. The fraction of this value for the total surface area could be negligible. And then the 2-D draft was revolved to make a 3-D model. To make a flat wall in the minor axis, the AutoCAD command “slice” was used.

In process sequence design, the diameter of a designed cup is determined by the drawing coefficient. And then the height of the product must be calculated according to surface area constancy. In this study, by creating 3-D part modeling for a deformation zone, the surface area is automatically computed in AutoCAD. Thus, the surface area calculation was used to design the blank’s shape for a non-axisymmetric deep drawing product with an elliptical shape. The surface area of the non-axisymmetric elliptical product is calculated by the 3-D modeling module.

2.3 Blank Design Module

The best way to determine the blank shape and dimensions in industrial practice is to use accumulated know-how and trial-and-error method; because the blank shape for elliptical deep drawing products has not been mathematically established yet. Usually, the strain distribution in the diagonal directions is decreased due to cutting off the corners of the blank sheet. To consider this phenomenon, the blank design module was constructed by using the surface area constancy to coincide with the industrial practice. Figure 4 shows the blank geometry (similar to blank cut off) proposed in this study. The blank dimensions were determined using the equivalent area of the product in the 3-D modeling module.

One of the most important steps in determining the shape of the blank and its dimensions in the deep drawing process is to calculate the surface area of the product. Usually, the surface area of axisymmetric products is calculated by mathematical or graphical methods. However, in the case of non-axisymmetric elliptical products, it is difficult to calculate the exact surface area due to errors caused by separated components. Fortunately, it is possible for non-axisymmetric elliptical products to be recognized by the geometry of the long and short side by drafting them as another two layers with AutoCAD software.

There is no formulated blank shape for a deep drawing product with a non-axisymmetric shape. Generally, a circular blank is designed for cylindrical and square cup deep drawing products. For a rectangular cup deep drawing, the configuration of the blank is obtained by flattening the geometric elements and by means of numerical formulas. Kim and Kobayashi (1986) used an approximate geometric method to determine the optimal blank shape for a rectangular cup. Bae et al. (1998) experimentally determined the optimum blank shape for a rectangular cup drawing. Cutting the corners of the blank in a diagonal direction has often suggested as a way to improve formability in rectangular blank. It was observed

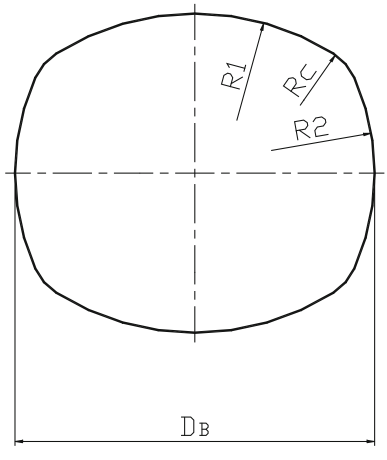


Fig. 4 Blank shape for elliptically shaped product

that the strain distribution was reduced when the corners of a blank were cut off in a diagonal direction. Where the final product is a non-axisymmetric shape that consists of a circular arc in the major axis and a straight line in the minor axis, the blank shape designed by trial-and-error was fabricated simply by calculating the surface area of the final product, and then the size of the final blank was determined by many experiments.

2.4 Process Planning Module

The deep drawing processes are composed of cylindrical drawing, preform, and top-part deep drawing. The preform process is a critical stage in the process sequence of a motor frame product (the initial shape of a circular cup is changed to an elliptical shape with straight walls), because metal flow is different for variation of direction during forming. The process planning module was optimized by interviewing field engineers to obtain industrial practice data (Choi et al. 1999a, b, 2000a, b). Thus, an appropriate drawing coefficient must be maintained in the preform process to prevent a local thickness reduction. To produce this preform, several methods of process design of the intermediate operation were proposed. Figure 5 represents the result of the surface area calculation for 3-D modeling of a non-axisymmetric deep drawn product. Figure 6 shows a photograph of an actual non-axisymmetric deep drawing product (t = 1.6 mm). Figure 7 represents the design result of the cross-section for a non-axisymmetric deep drawn product.

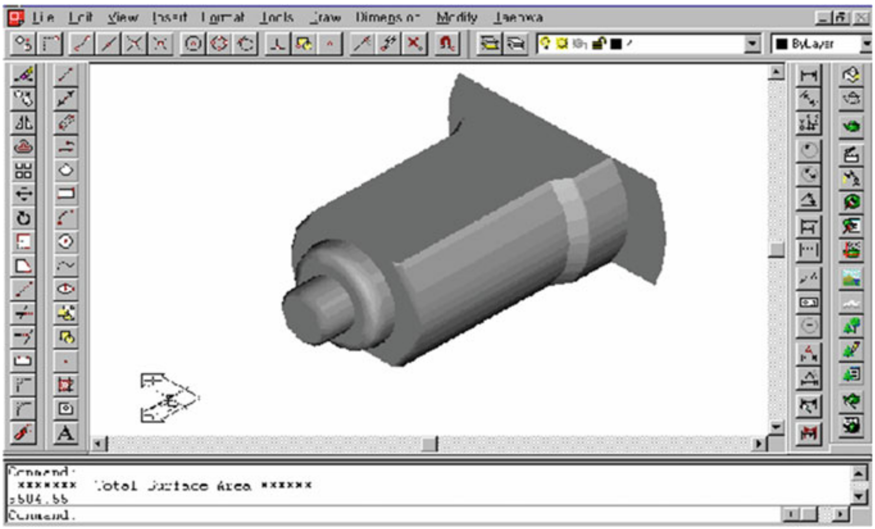


Fig. 5 The result of the surface area calculation for the three-dimensional modeling of non-axisymmetric deep drawn product (t = 1.6 mm)

Fig. 6 Photograph of an actual non-axisymmetric deep drawing product (t = 1.6 mm)

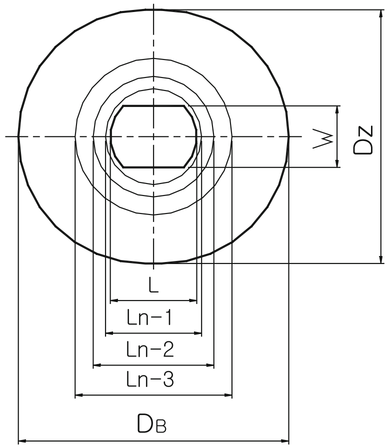


Fig. 7 Design result of cross-section for non-axisymmetric deep drawn product

In general, in the case of cylindrical deep drawing process, Romanowski's drawing coefficient, based on the ratio of thickness and blank diameter, is used (Lange 1985; David 1990). However, in the case of non-axisymmetric elliptical deep drawing products such as an elliptical cup, the drawing coefficient is insufficient to verify the relationship between the process sequence and the variable. To solve this problem, we modified the drawing coefficient table based on the characteristics of the non-axisymmetric elliptical deep drawing products and equation for the first drawing coefficient.

It is known that the cups fail due to tearing in a punch shoulder, which has a radius less than twice the thickness of the blank. If R_p is more than 10 times the thickness, stretching may be introduced. A sharper punch and die with a greater nose radius must be used. And for a constant punch shoulder radius, the maximum load is decreased as the die radius is increased. For a constant die radius, however, the maximum punch loads do almost never change with variations in the punch radius. Consequently, within the region $4t < R_p, R_d < 10t$ the radius does not significantly affect the limiting drawing ratio. Therefore, the punch and die radii must be between 4 and 10 times in thickness for the first drawing in cylindrical deep drawing. And it is known that punch and die radii are c (coefficient, $0.6 < c < 0.8$) times the previous radius in the redrawing process. Owing to the characteristics of the forming sequence for non-axisymmetric elliptical deep drawing products, the punch and die radii in the study are c (coefficient, 4 or 6) times the thickness in the first drawing (Eary and Reed 1974; Edward 1991).

3 Production Rules of the Knowledge-Based System

The computer-aided knowledge-based system can be constructed on experienced knowledge of field engineers. The acquisition of knowledge and the representation of it are two of the most important tasks in the construction of the system. By interviewing field engineers, production rules are generated and developed. During the interviews, data are recorded, transcribed, and then checked with them before formalizing the rules. In addition, plasticity theories, handbooks, and experimental results were also referred. The characteristics of process sequence in elliptical deep drawing products were scientifically investigated. Production rules are also based on a decision tree which takes the form of “IF(conditions) THEN(actions).” The cross-section of product body, drawing coefficient, punch radius, and die radius are considered as main design parameters. Rules that are different from those for rotationally symmetric deep drawing products are given here.

- Rule 1 If the cross-section of deep drawing products was a circle in the major axis and a straight line in the minor axis, then the product is defined as elliptical deep drawing product.
- Rule 2 The surface area of the product was calculated by the use of three-dimensional modeling of the product based on neutral axis of the thickness.
- Rule 3 The surface area of the product is the same as that of the blank.
- Rule 4 The volume of the product is the same as that of the blank.
- Rule 5 If the input geometry is elliptical, then the blank shape is basically oval.
- Rule 6 In calculating the drawing coefficient, the blank diameter in the major axis was used.
- Rule 7 In computing the blank size, the trimming allowance is 1.25 times the thickness of the blank.
- Rule 8 The process sequence consists of cylindrical drawing, preform, and top-drawing process.

Rule 9 After forming the final product in deep drawing process, there are only secondary operations such as trimming and piercing.

Rule 10 If a process is the first drawing, then a drawing coefficient must be applied in the range 0.54–0.58.

Rule 11 If a process is the last cylindrical drawing, then the next process is defined as preform.

Rule 12 If a process is preform, then a drawing coefficient must be applied in the range 0.87–0.9 with the body dimension of the major axis.

Rule 13 If a process is preform, then a punch radius between cup wall and top-part must be applied in the range 8R-10R.

Rule 14 If a process is preform, then the product height is determined by the surface area constancy.

Rule 15 If a process is the first process in top-part drawing, then the process is called bottoming and a drawing coefficient is applied in the range 0.64–0.7 with the body dimension of the major axis. After the bottoming process, the drawing coefficient is used as the redrawing coefficient.

Rule 16 If a process is the last process in top-part drawing, then a drawing coefficient of 0, 95 must be applied.

Rule 17 A drawing process sequence for an elliptical shape product on AutoCAD represents the side view of the product in orthogonal axes. The description shows the geometry of the major axis on the lefthand side and for minor axis on the righthand side.

Rule 18 The surface area of the deformation zone is the same as that of the deformed zone.

Rule 19 If the final geometry of an elliptical-shaped deep drawing product is input to the knowledge-based system, a sequence of operations should be produced where each operation produces one new deformation zone.

Rule 20 If a process is the first drawing, then R_p and R_d are calculated as follows:

$$R_p = C_{fp} \times t$$
$$R_d = C_{fd} \times t$$

where,

$$C_{fp} = 6.0$$
$$C_{fd} = 4.0$$

t initial thickness of material

Rule 21 If a process is redrawing in cylindrical cup drawing, then R_p and R_d are calculated as follows:

$$R_p = \frac{(D_{n-1} - D_n)}{2} \times C_{rp}$$
$$R_d = \frac{(D_{n-1} - D_n)}{2} \times C_{rd}$$

where,

$$1.5 < C_{rp} < 2.0$$
$$1.0 < C_{rd} < 1.4$$

D_n a present cup diameter
D_{n-1} a previous cup diameter

Rule 22 If a process is preform, then R_p and R_d in the major and minor axes are calculated as follows:

$$R_p = \frac{(Dcyl - DmS)}{2} \times C_{pr} \quad R_d = \frac{(Dcyl - DmL)}{2} \times C_{dr} \quad \text{for major axis}$$

$$R_p = \frac{(DmL - DmS)}{2} \times C_{pr} \quad R_d = \frac{(Dcyl - DmS)}{2} \times C_{dr} \quad \text{for minor axis}$$

where,

$$1.0 < C_{pr} < 2.0$$
$$1.5 < C_{dr} < 2.0$$

D_{mL} Body diameter of the major axis
D_{mS} Body dimension of the minor axis
D_{cyl} Diameter of the last cylindrical cup

Rule 23 If a process is top-part drawing, then Rp and Rd are calculated as follows:

$$R_p = \frac{(D_{n-1} - D_n)}{2} \times C_{tp}$$
$$R_d = \frac{(D_{n-1} - D_n)}{2} \times C_{td}$$

where,

$$0.8 < C_{tp} < 1.5$$
$$1.0 < C_{td} < 1.5$$

D_n a present cup diameter
D_{n-1} a previous cup diameter

Rule 24 If a process is top-part drawing, then the body dimension of the minor axis and the diameter of the top-part are considered as comparative dimensions.

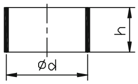
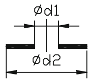
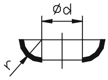
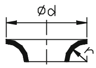
4 Results and Discussion

The product applied in this system is a motor frame product with elliptical shape, which is completely produced by multistage deep drawing process and secondary operations such as piercing and trimming. The product geometry in the last deep drawing process was used for the input shape of the system. The height of the product should be designed on the basis of surface area constancy. In this system, a 3-D model of top-part considering the above mentioned rules was used to determine an accurate height.

4.1 The Surface Area Calculation

The surface area of axisymmetric cylindrical product is calculated by mathematical or 3-D modeling methods. The shape and dimensions of the blank were designed based on identical surface area. The surface area calculated by 3-D modeling method is the same as the mathematical method. In axisymmetric cylindrical products, it is possible for mathematical or 3-D modeling methods to calculate the exact surface area. Figure 8 shows a calculating formula of axisymmetric deep drawn products. However, in the case of non-axisymmetric elliptical products, it is difficult to calculate the exact surface area due to errors caused by separated components. Also the mathematical method for calculating the surface area should allow for a little more time to calculate the surface area of separated components. The blank shape and dimensions were designed based on identical surface area calculated by the 3-D modeling module. The mathematical method should allow for a little more time to calculate the approximate surface area of separated components of the non-axisymmetric elliptical product, but it is impossible to calculate the exact

Fig. 8 A calculating formula of axisymmetric deep drawn products

Name	Shape	Surface Area
Cylinder		A=3.1416dh
Ring		A=0.7854(d2*d2-d1*d1)
Convex		A=4.9348rd+6.2832r*r
Concave		A=4.9348rd-6.2832r*r

surface area because of the characteristics of the discontinuous lines. However, it is possible for the 3-D modeling method to calculate the exact surface area rapidly.

4.2 *Drawing Coefficient*

In general, in the case of the cylindrical deep drawing process, Romanowski's drawing coefficient, which is based on the ratio of thickness and blank diameter, is used. However, in the case of non-axisymmetric deep drawing product such as non-circular cup, though the drawing coefficient is defined as the ratio of width and blank size in rectangular deep drawing process, it is insufficient to verify the relationship between process sequence and variable. To solve this problem, we modified the drawing coefficient table based on the characteristics of elliptically shaped deep drawing products and the equation for the first drawing coefficient. Table 2 shows the modified drawing coefficient for cylindrical deep drawing proposed in this system. Table 3 shows the modified drawing coefficient for top-part deep drawing.

Table 2 Modified drawing coefficient for cylindrical deep drawing

Drawing coefficient	D_{mL}/D_B		
	0.27 ~ 0.31	0.31 ~ 0.335	0.335 ~ 0.35
M1	0.53 ~ 0.55	0.55 ~ 0.58	0.58 ~ 0.60
M2	0.76 ~ 0.78	0.78 ~ 0.79	0.79 ~ 0.80
M3	0.79 ~ 0.80	0.80 ~ 0.81	0.81 ~ 0.82
M4	0.81 ~ 0.82	0.82 ~ 0.83	0.83 ~ 0.85
M5	0.84 ~ 0.85	0.85 ~ 0.86	0.86 ~ 0.87

D_B Blank diameter for major axis

Table 3 Modified drawing coefficient for top-part deep drawing

Drawing coefficient	D_F/D_{mS}		
	0.39 ~ 0.42	0.42 ~ 0.47	0.47 ~ 0.55
M1	0.64 ~ 0.65	0.65 ~ 0.67	0.67 ~ 0.70
M2	0.76 ~ 0.78	0.78 ~ 0.79	0.79 ~ 0.80
M3	0.79 ~ 0.80	0.80 ~ 0.81	0.81 ~ 0.82
M4	0.81 ~ 0.82	0.82 ~ 0.84	0.84 ~ 0.85
M5	0.84 ~ 0.85	0.85 ~ 0.86	0.86 ~ 0.87

D_F Body diameter for top-part deep drawing

In designing the preform process, good formability was obtained when the drawing coefficient was approximately 0.9. Therefore, the system was rearranged using the drawing coefficient related to the process sequence number. Each process transforms the component into multistage cups by using the production rules for non-axisymmetric deep drawing. The drawing coefficient is a major factor in formability of deep drawing product. Process parameters such as the punch radius, die radius, and thickness of sheet metal are satisfactory for determination of the drawing coefficient.

4.3 Punch and Die Radii

Generally, punch and die radii used are for 4–10 times as thick as first drawing in cylindrical deep drawing. However, owing to the characteristics of process sequence for elliptically shaped products, the punch and die radii applied in this system were 4–6 times as thick as first drawing. The blank shape and dimensions were designed based on the identical surface area calculated in the 3-D modeling module. The calculated results of the surface area for the non-axisymmetric product are shown in Table 4.

Figure 9 shows input shape of the system in the major and minor axes. Figure 10 shows Graphic User Interface (GUI) of the system developed in the study. The input to the system is only the final product geometry which modeling was produced using AutoCAD software along the major and minor axes of the final product. The system is convenient to construct, modify, and extend because of its modularity. Figure 11 shows the input data to the system in the dialogue control box. Figures 12 and 13 illustrate the results of the knowledge-based system for

Table 4 Calculated results of the surface area for the non-axisymmetric deep drawing product

Method	Surface area (mm^2)
Mathematical calculation	9,557
Three dimension model	9,504.55

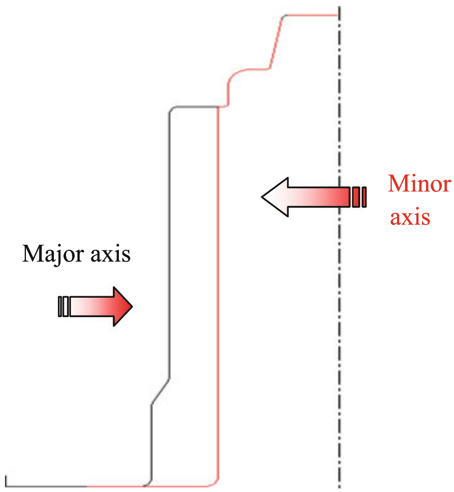


Fig. 9 Input shape of the system in the major and minor axes

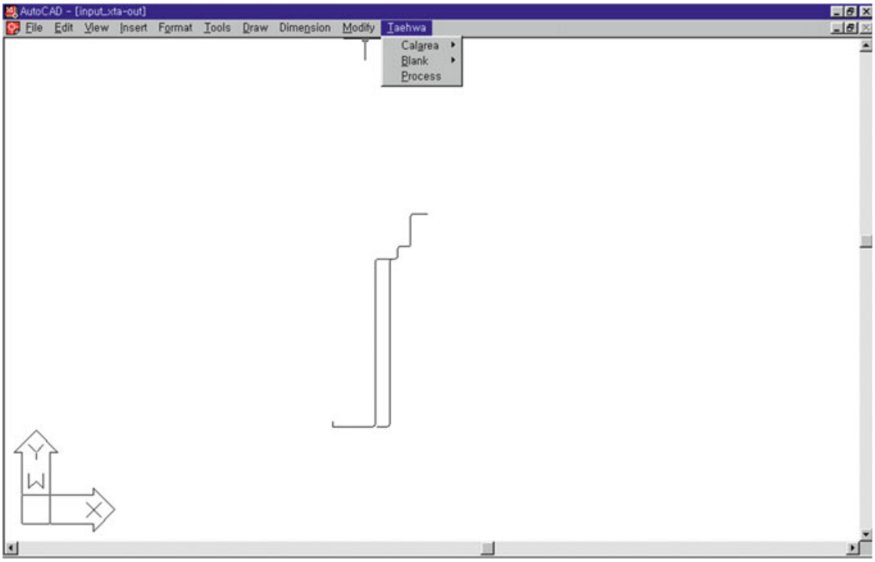


Fig. 10 Graphic user interface of the knowledge-based system

non-axisymmetric deep drawing product. The results of the system have good agreement with those of the actual non-axisymmetric elliptical deep drawing product. In this study, the knowledge-based system was constructed using the production rules. The process sequence in the design of the preform is very important for producing the elliptically shaped products. Consequently, designer's

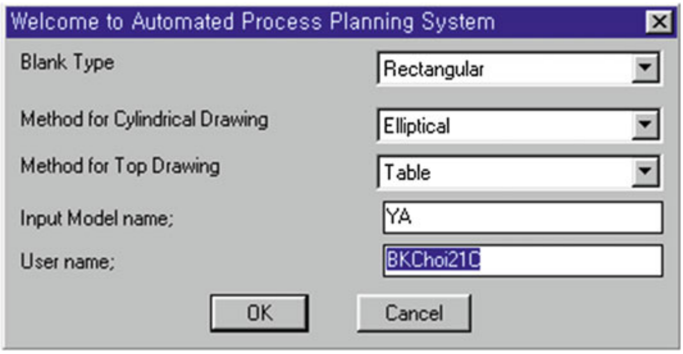
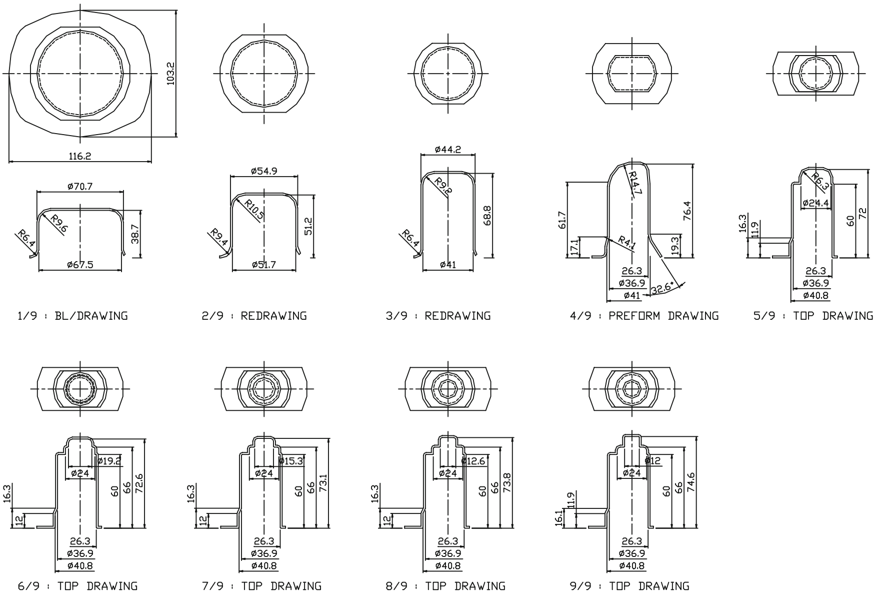


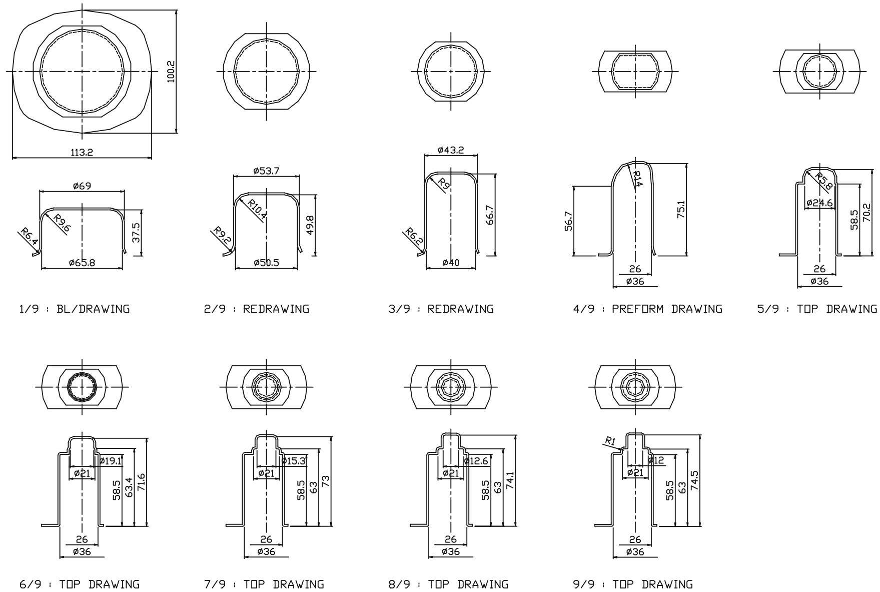
Fig. 11 Input data in the dialogue control box



Process	1	2	3	4(L)	4(S)	5	6	7	8	9
Draw Coeff.	0.58	0.77	0.79	0.9	0.64	0.66	0.78	0.8	0.82	0.95

Fig. 12 The result of the knowledge-based system for non-axisymmetric deep drawing products (I)

decision on the number of die and forming conditions plays a critical role in process planning and die manufacturing. The flexibility of the knowledge-based system proposed in present study was improved by introducing helpful modules to process variables which are expected to reduce the lead-time for manufacturing and improve the accuracy of products in the future. Finally, there is obviously more than



Process	1	2	3	4(L)	4(S)	5	6	7	8	9
Draw Coeff.	0.58	0.77	0.79	0.9	0.65	0.68	0.78	0.8	0.82	0.95

Fig. 13 The result of the knowledge-based system for non-axisymmetric deep drawing products (II)

one possible solution for the production of a given component. The system is capable of offering alternative solutions in blank and drawing coefficients. When predicting an ambiguous result, the system will request that the user selects between the options, thus enhancing the flexibility of the system.

5 Conclusion

This study focused on acquiring and quantifying process design variables such as the drawing coefficient, punch and die radii for elliptically shaped deep drawing products. Based on the development of the knowledge-based system for non-axisymmetric elliptical deep drawing process, the results can be summarized as follows:

(1) The knowledge-based system in this work was expanded from axisymmetric to non-axisymmetric products and a system for multistage elliptically deep drawing products was constructed.

(2) Production rules, based on industrial practices, were generated for elliptically shaped deep drawing products, and a system based on these rules was constructed for non-axisymmetric elliptical deep drawing process.
(3) Three-dimensional modeling for non-axisymmetric elliptical products was used to calculate the total surface area. A modified Entity_List was proposed to make the modeling for non-axisymmetric elliptical products easy.
(4) The blanks were designed with identical surface area calculated by the 3-dimensional modeling module. The blank shape and dimension were verified by experimental results, which studied the appearance of the product and the distribution of thickness strain. The designed blanks were applied without defects in this process.
(5) Modified drawing coefficient based on the characteristics of elliptically shaped deep drawing products and the equation for the first drawing coefficient were proposed for application to elliptical shape parts.
(6) The blank shape and dimensions were designed based on identical surface areas calculated in the 3-D modeling module. The results of the knowledge-based system have good agreement with those of industrial practice.

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An Expert System for Automatic Design of Compound Dies

Sachin Salunkhe, Shailendra Kumar and Hussein M.A. Hussein

1 Introduction

Compound die is widely used in sheet metal industries for manufacturing of pierced blanks with good accuracy. A typical compound die is shown in Fig. 1. The press speed (strokes per minute) for compound dies is kept only slightly lower than the single-operation dies; therefore, production time and labor cost per piece decrease almost in proportion to the number of operations done on a compound die. Design of compound die is usually carried out by highly experienced die designers in sheet metal industries. Die design includes various activities such as manufacturability assessment, process planning, selection of die components, and die modeling. Traditional procedure of design of compound die is manual, tedious, time-consuming, error-prone, and highly experienced based (Ann and Kai 1994; Kim et al. 2001). A die designer needs to spend many hours consulting hand books, going through empirical formulae, perusing tabulated and graphical information, and making calculations before arriving at practical designs. Further nowadays sheet metal industries are also facing problems due to scarcity of experienced die designers and their frequent mobility. Various computer aided design (CAD) systems are being used in sheet metal industries since last 30 years. These

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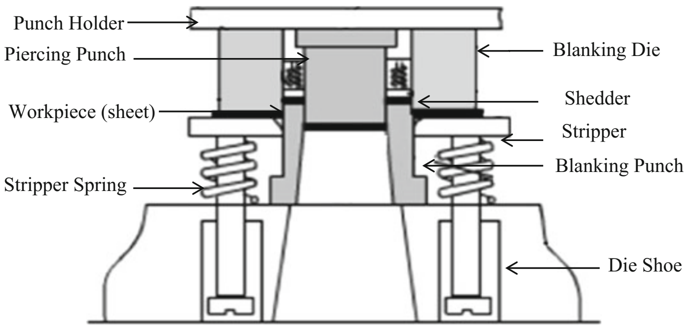


Fig. 1 A typical compound die

systems provide some aid to die designers to perform calculations, storage and retrieval of data, visualization of part geometry, and die drafting. But human expertise is still needed to arrive at the final design. Also, the cost of these softwares is high and cannot be affordable by small-scale sheet metal industries.

To overcome the above problems an expert system needs to be developed for automatic design of compound dies. Expert system is one of the most powerful tools of artificial intelligence (AI) for solving engineering problems which are complex, time-consuming, and highly experience based (Garzotto and Paolini 1989). Expert systems are computer programs embodying knowledge about a narrow domain for solving problems related to that domain (Peter Jackson Peter 1998). As shown in Fig. 2, an expert system comprises three main elements—(i) knowledge base, (ii) inference engine, and (iii) user interface. The knowledge base contains domain knowledge, which may be expressed as any combination of IF–THEN rules, frames, objects, factual statements, procedures and cases. The inference engine allows manipulating the stored knowledge for solving problems. The user interface enables an expert system to interact with the user.

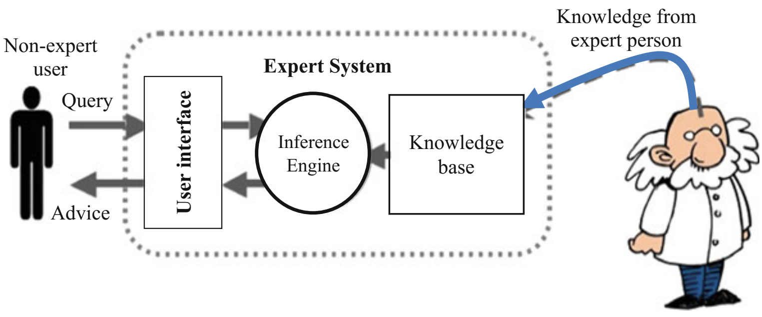


Fig. 2 Expert system (www.igcseict.info)

The basic idea behind the development of an expert system is simply that expertise, which is the vast body of task-specific knowledge, is transferred from human experts to a computer. The computer can make inferences and arrive at a specific conclusion. There is spectrum of applications of expert system in manufacturing (Jayaraman and Srivastava 1996). But only very few of them are concerned to the design of sheet metal dies (Kumar 2006; Hussein 2007). Design of compound die is tedious, time-consuming, and highly experience-based process. Sheet metal industries need to preserve experienced knowledge of die designers in the form of an expert system integrated with a CAD system. Such integration would help to reduce the complexity and time taken in skill intensive tasks such as die design. Furthermore, such a system would assist young die designers and can act as an independent training tool for beginners.

The present chapter describes an expert system developed by authors for automatic design of compound dies. The next section of this chapter describes R&D efforts in the domain of die design.

2 Literature Review

Worldwide researchers have applied efforts for development of computer-aided systems for die design (Kashid and Kumar 2012). For example, Nakahara et al. (1978) proposed a system for manufacturability assessment of sheet metal parts produced on progressive die. Adachi et al. (1983) proposed an integrated CAD system for progressive dies. Altan (1987) described some of the interactive CAD/CAM systems for die design and manufacturing. Xiao et al. (1990) developed an expert system using a set of production rules and frames for designing axisymmetric deep drawing parts. Tisza (1995) reported to develop metal forming expert system called METEX using principles of group technology for process planning of multistage forming processes. Further, Tisza (2007) proposed two main approaches one of them may be regarded as knowledge-based process planning, whilst the other as simulation-based process planning. Nee and Foong (1992) reviewed the techniques employed in design of progressive die punches and made an attempt to link the programs together to form a useful package for design of progressive dies for bending and forming operations. Prasad and Somasundaram (1992) developed a computer-aided die design system labeled as CADDS. Hoffmann et al. (1992) developed a bending-sequence generator using expert system approach to computerize the process planning of sheet metal parts. Fang and Tolouei-Rad (1994) proposed a rule-based expert system for process planning of complex circular shells produced by deep-drawing process. Nee (1994) proposed a CAD system for automation of progressive die design. Lin and Peing (1994) proposed an expert system on a PC/AT for sheet metal bending design. Esche et al. (1996) developed an expert system for axisymmetric parts produced by deep drawing process. Yeh et al. (1996) developed a rule-based and feature-based design advisor for sheet metal parts called product modeler (ProMod-S). Sing and Rao

(1997) proposed a KBS for process planning of axisymmetric deep drawing using decision tables. Cheok and Nee (1998a) developed a computer-aided system for progressive die design. Further they (Cheok and Nee 1998b) proposed a KBS for intelligent design of progressive dies. Kim et al. (1998) developed an expert system for design of draw die. Singh and Sekhon (1999) reported to develop an expert system for selection of an optimal process plan for sheet metal operations. Choudhary and Allada (1999) developed an integrated PC-based CAD/CAM system for design of precision punches and dies for small-scale manufacturers. Park et al. (1999) developed a prototype CAD/CAM system for axisymmetric deep drawing processes in simple action press. Park (1999) proposed an expert system for deign of progressive dies for electron gun grid parts. Choi et al. (2000) developed an automated CAD system for progressive working of irregular-shaped metal products and lead frame for semiconductors. Kim et al. (2001) developed a knowledge-based computer aided system for design of precise progressive die for production of lead frame of semiconductor chip. Kang and Park (2002) proposed a computer-aided process planning (CAPP) system for rotationally symmetric deep drawing products. Choi et al. (2002) developed a modular design support system for axisymmetric deep drawing process. Liu et al. (2003) presented a method for automatic extraction of features from arbitrary solid model of sheet metal parts. Sutt et al. (2004) proposed a design environment for design of progressive cutting dies using mid-range level CAD package. Ismail et al. (2005) proposed a new technique for feature recognition from B-rep (Boundary Representation) models. This technique identifies solid and void 'sides' of a boundary entity, and extracts cylindrical-based and conical-based features. Kim et al. (2006) developed an expert system for the design of draw die for automotive industry. Lee et al. (2006) proposed an assessment system consisting of a knowledge-based geometric analysis module, a finite element module and a formability analysis module. Kumar et al. (2006) developed a rule-based expert system for assessing manufacturability of sheet metal parts. Emad and Kamrani (2006) proposed an intelligent feature recognition methodology for automatic feature recognition of 3-D prismatic parts. Kumar and Singh (2007a, b) proposed production rule-based knowledge base system (KBS) modules for selection of progressive die components and die modeling. They (Kumar et al. 2008) also developed a KBS for design of blanking dies. Rahamani and Arezoo (2007) proposed hybrid graph-based and hint-based techniques for automatic feature extraction from solid model. Zhou et al. (2007) used feature recognition concept for integration of CAD and Computer Aided Process Planning (CAPP). A fully integrated CAD/CAM/CAE system was developed by Lin and Kuo (2008, 2011) for stamping dies of automotive sheet parts. Further they (2011) used Finite Element Analysis (FEA) and the fuzzy-based taguchi method for design of ribs for drawing dies by combining. Giannakakis and George-Christopher (2008) developed an expert system for process planning and die design of sheet metal cutting and piercing operations. Molcho et al. (2008) described a computer-aided manufacturability analysis (CAMA) tool for capturing knowledge from manufacturability point of view. Hussein and Kumar (2008) proposed a computerized retrieval system for sheet metal parts. Rameshbabu and Shunmugam

(2009) presented a hybrid approach to recognize the manufacturing features from 3-D CAD model of STEP AP-203. Sunil et al. (2010) developed the new hybrid approach for recognizing the interacting feature from B-rep CAD model. Kumar and Singh (2011) developed an automated design system for progressive dies using production rule-based KBS approach. Naranje and Kumar (2011) developed a KBS for manufacturability assessment of deep drawn sheet metal parts. Wang et al. (2012) proposed a feature recognition system to identify shape and size of different features from 3-D model of part. Su and Ma (2012) developed a CAD system for design of bending die. Naranje and Kumar (2012) proposed a KBS for selection of components of deep drawing die. Further, they (2014) developed KBS for automated design of deep drawing die for axisymmetric parts. Potocnik et al. (2012, 2013) developed KBS for supporting the design of a press plate. Hussein et al. (2013) used STEP AP-203 CAD model for feature recognition of 3-D prismatic parts. Panghal and Kumar (2013) developed a KBS for manufacturability assessments of bending parts. Lin et al. (2013) described KBS for progressive dies with drawing, bending, and punching operations. Hussein (2014) proposed a CAD system for design of blanking dies. Neugebauer et al. (2015) developed new feature extraction and processing methods for process planning of forming operations.

Die designers in sheet metal industries are using some commercial CAD softwares such as NX Progressive Die Wizard, Solid Edge, AutoForm, Technos, Optimal Programs, Metamation, Missler Software (Top Solid), Auto-Trol, ToolDesigner MetalCAD, ADAMS DieMaster, ESPRIT, CADD Station family, MICRO-UNICAD, VISI, Striker system, SolidWorks, Dassault Systèmes (CATIA), CADCEUS, etc. The capabilities of some CAD systems being used for die design are discussed as under.

M/s Vero-Software, USA developed a specialized CAD/CAM software 'VISI-Progress' for the design of progressive dies and press tools. It can directly interface with various platforms such as IGES, STEP, Parasolid, ACIS, CATIA V4 and V5, Pro/Engineer, Unigraphics, Solidworks, Solid Edge, Inventor, and Mechanical Desktop. The limitation of this software is it's over automation and requires trained person to operate this software. M/s ESPRIT, USA developed press tool software for design of progressive and compound dies. Developed software is composed with Application Programming Interface (API) based on the Microsoft Component Object Model (COM) and Microsoft Visual Basic for Applications. This software is costly and it is not parametric in nature. 'UG-NX Progressive Die Wizard' is the progressive die design software of M/s PLM Siemens Inc., USA (formerly M/s Unigraphics Solutions). Features of this software are automated punch creation, broad CAD coverage, excellent assembly tools, excellent drafting facility and library of many standard catalog items. But the major limitations of this system are that it requires solid model as initial part geometry (STEP/IGES format), complex to use, extensive training is required, costly, highly automatic which kills designer creativity, unable to provide technical support at initial stage of design process and developed for very large die shops. M/s Dassault Systèmes (CATIA), France developed specialized Toolmaker software for design of dies. This software works in conjugation with IGES, STEP, CATIA V4 and V5, Pro/Engineer, Unigraphics, Solidworks, Solid Edge and Inventor. Limitations of this software are that it requires highly trained person to operate, cost is very high and takes much time during assembly of die.

Form the literature review, it can be concluded that worldwide researchers have applied efforts to develop computer-aided systems for single-operation dies, progressive dies, and deep drawing dies. But these systems are not capable to automate all activities of traditional die design process. Further these systems need considerable interactive inputs from experienced die designers, and finally to take appropriate decisions at various stages of die design process including process planning, selection of die components, and die modeling. No system has been reported in the literature which is focused on automation of design of compound dies. Therefore, there is enough scope of research in this domain to assist die designers of sheet metal industries. The present chapter describes an expert system developed by authors for automatic design of compound dies.

3 Proposed Expert System: ESIDCD

The system labeled as ESIDCD (*E*xpert *S*ystem for *I*ntelligent *D*esign of *C*ompound *D*ies) is organized into the following subsystems and modules.

1. Subsystem namely PPCD (*P*rocess *P*lanning of *C*ompound *D*ie) is developed for process planning of sheet metal parts produced on compound die. It consists of five modules as follows:

   (i) Module STSEL for selection of strip size,
   (ii) Module PUNFR for determination of punch force,
   (iii) Module CLR for determination of clearance between punch and die,
   (iv) Module OPRID for operation identification, and
   (v) Module OPRSEQ for determining operation sequence.

2. Subsystem namely CDCOMP (*C*ompound *D*ie *C*omponents) is developed for selection of type and size of components of compound die. It consists of eight modules as follows:

   (i) Module DBLOCK for selection of die block,
   (ii) Module DGAGE for selection of die gage,
   (iii) Module STRP for selection of stripper,
   (iv) Module STSPR for selection of stripper springs,
   (v) Module CDPUN for selection of punches,
   (vi) Module DISET for selection of die-set,
   (vii) Module FSTN for selection of fasteners, and
   (viii) Module KNKB for selection of knockout bar.

3. Subsystem, namely, AUTOMODCD (*Auto*matic *Mod*eling of *C*ompound *D*ie) is developed for automatic modeling of compound die. It is structured in the form of following modules:

   (i) Module CDDBLOCKMOD for modeling of die block,
   (ii) Module CDGAGEMOD for modeling of die gage,
   (iii) Module CDSTRPMOD for modeling of stripper,
   (iv) Module CDSTSPR for modeling of stripper springs,
   (v) Module CDPUNMOD for modeling of punches,
   (vi) Module CDDISETMOD for modeling of die-set,
   (vii) Module CDKNKBMOD for modeling of knockout bar,
   (viii) Module CDBAMOD for modeling of bottom die assembly of compound die, and
   (ix) Module CDTAMOD for modeling of top die assembly of compound die.

Organization of the proposed system is shown in Fig. 3. The system overall consists of more than 1500 production rules of 'IF–THEN' variety. The rules are coded in AutoLISP language. Various subsystems and modules of the proposed system are briefly described as under.

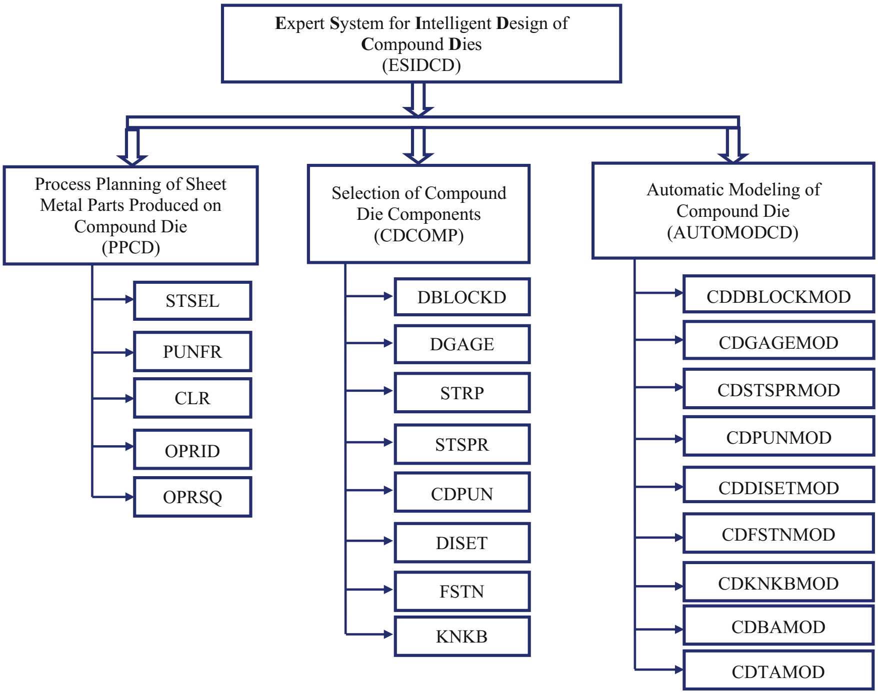


Fig. 3 Organization of the proposed system ESIDCD

3.1 Subsystem PPCD

The subsystem PPCD has been developed to automate the process planning of sheet metal parts produced on compound die. This subsystem consists of five modules. A sample of production rules incorporated in the proposed system is given in Table 1. Execution of the sub-system is shown in Fig. 4. First of all it reads data file FE.DAT generated during execution of system of automatic feature extraction (as described in Chap. 3). It also recalls part data file namely PD.DAT to read part details. The first module, namely, STSEL is developed for selection of size of strip. The module displays the required length and width of strip. These outputs are stored automatically in a data file, namely, STSEL.DAT. The next module labeled as PUNFR is developed for determining punch force required to manufacture sheet metal parts. To calculate punch force, the following formula is coded using AutoLISP language:

Punch force $(F) = t \times \tau \times a$
where t = Sheet thickness in mm
τ = Shear strength of sheet material in N/mm^2
a = Area of cutting feature in mm

The output of this module in the form of required punch force is stored automatically in a data file labeled as PUNFR.DAT. The third module namely CLR is developed for determining die-angle, die-land, and cutting clearance between punch and die. The output of the module in form of die-angle and die-land are stored in a data file DLA.DAT and cutting clearance between punch and die is stored in another data file namely CLR.DAT. The next module, namely, OPRID is developed for identification of sheet metal operations required for production of sheet metal part on a compound die. A feature library has been developed for the proposed module. This feature library is displayed on AutoCAD screen on loading the module through GUI. The module invites the user to select the geometrical features required for manufacturing the part from feature library. Output of this module in the form of required sheet metal operations are stored in a data file, namely, OPRID. DAT. The last module labeled as OPRSQ is developed for determination of proper sequence of operations to manufacture sheet metal part correctly and efficiently. The module takes required inputs automatically from the data file OPRID.DAT generated during execution of previous module. Finally, it displays the operation sequence for the user. This output is stored in a data file labeled as OPRSQ.DAT.

Table 1 A sample of production rules incorporated in the subsystem PPCD

S. No.	IF	THEN
1	Sheet thickness in mm ≤ 1.0; and Size of outer shape of part in mm ≤ 25.0; and Sharp edge exists in the edge perpendicular to the moving direction of the strip	Select strip width in mm = (Size of outer shape of part + 2.0)
2	Sheet thickness in mm ≤ 1.0; and Size of outer shape of part in mm > 75.0; and Size of outer shape of part in mm ≤ 150.0; and Sharp edge exists in the edge perpendicular to the moving direction of the strip	Select strip width in mm = (Size of outer shape of part + 4.0)
3	Sheet thickness in mm > 1.0; and Sheet thickness in mm ≤ 2.0; and Size of outer shape of part in mm ≤ 25.0 Sharp edge exists in the edge perpendicular to the moving direction of the strip	Select strip width in mm = (Size of outer shape of part + 2.6 times of sheet thickness)
4	Sheet thickness in mm > 1.0; and Sheet thickness in mm ≤ 2.0; and Size of outer shape of part in mm > 25.0; and Size of outer shape of part in mm ≤ 75.0 Sharp edge exists in the edge perpendicular to the moving direction of the strip	Select strip width in mm = (Size of outer shape of part + 4.0 times of sheet thickness)
5	Sheet thickness in mm ≤ 1.6	Set die-angle = 0.25°; and Die-land = 3.5 mm
6	Sheet thickness in mm > 1.6; and Sheet thickness in mm ≤ 4.5	Set die-angle = 0.5°; and Die-land = 4.0 mm
7	Sheet thickness in mm > 4.5	Set die-angle = 0.75°; and Die-land = 5.5 mm
8	Sheet material = Stainless steel [AISI 1090]; and Shear strength = 600–650 N/mm^2; and Sheet thickness in mm ≤ 1.0; and Hardness of sheet material = 50–55 HRC	Set clearance all around = 5.4 % of sheet thickness
9	Sheet material = Brass; and Shear strength = 350–400 N/mm^2; and Sheet thickness in mm ≤ 1.0; and Hardness of sheet material = 40–50 HRC	Set clearance all around = 3.8 % of sheet thickness
10	Minimum tolerance required on part in mm ≥ 0.001; and Maximum tolerance required on part in mm ≤ 0.02; and Design feature = hole or slot or oval hole or internal contour cut	Required operation = piercing
11	Minimum tolerance required on part in mm ≥ 0.001; and Maximum tolerance required on part in mm ≤ 0.02; and	Required operation = blanking

(continued)

Table 1 (continued)

S. No.	IF	THEN
	Design feature = external precision contour	
12	Required operations = piercing and blanking	Upper punch = piercing; and Lower punch = blanking
13	Required operations = notching and blanking	Upper punch = notching; and Lower punch = blanking
14	Required operations = notching and parting off	Upper punch = notching; and Lower punch = parting off

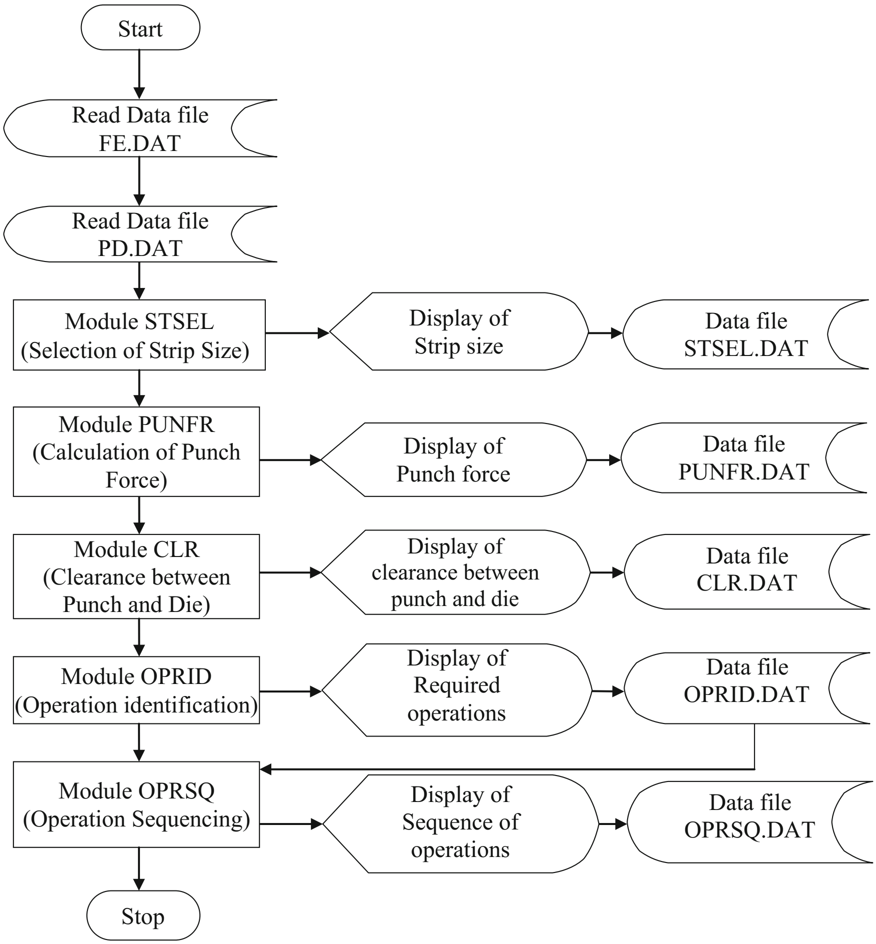


Fig. 4 Execution of subsystem PPCD

Table 2 A sample of production rules incorporated in the system CDCOMP

S. No.	IF	THEN
1	Size of blank in mm > 100.0; and Size of blank in mm ≤ 150.0; and Sheet thickness in mm ≤ 1.0; and Die material = Tool steel [SERVERKER 21]	Select width of die block in mm = (Strip width + 140.0); and Select length of die block in mm = (Strip length + 170.0)
2	Sheet thickness in mm ≤ 1.0; and Shape of die hole contour = smooth	Select distance between die gages in mm = (Strip width + 1.0); and Select width of die gages in mm = (Width of die block-distance between die gages); and Thickness of die gages in mm = 8.0
3	Sheet thickness in mm ≤ 1.0; and Shape of die hole contour = sharp inside corners	Select distance between die gages in mm = (Strip width + 1.0); and Select width of die gages in mm = (Width of die block-distance between die gages); and Thickness of die gages in mm = 8.5
4	Sheet thickness in mm > 0.2; and Sheet thickness in mm ≤ 0.8; and Stripping force ≤ 120,000 N	Select die size spring stripper (HRC 48–52) with strip width variation allowance in mm = 2.8; and Thickness of stripper plate in mm = 7.5; and Width of channel in mm = (width of strip + 2.8); and Channel height in mm = (2.0 times of sheet thickness +0.75)
5	Stripping force > 30,000 N; and Stripping force ≤ 40,000 N	Select circular spring; and Length of spring in mm = 220.0; and Outer diameter of spring in mm = 24.0; and Inner diameter of spring in mm = 16.0
6	Inner shape of part feature is circular; and Diameter of inner part feature in mm ≤ 25; and Sheet thickness in mm > 0.5; and Sheet thickness in mm ≤ 0.8	Select circular plain punch; and Diameter of circular punch in mm = (inner circular hole diameter + clearance between punch and die); and Select length of punch in mm = (inner circular hole diameter in mm + 45); and Select upper and lower punch plate thickness in mm = 14.0
7	Outer shape of part feature is square; and Dimension of outer part feature in mm > 100; and Dimension of outer part feature in mm ≤ 150; and Sheet thickness in mm > 1.2; and Sheet thickness in mm ≤ 1.7	Select square plain punch; and Dimension of square punch in mm = (outer square hole dimension - clearance between punch and die); and Select length of punch in mm = (outer dimension of square punch in mm + 180); and Select upper and lower punch plate thickness in mm = 16.0

(continued)

Table 2 (continued)

S. No.	IF	THEN
8	Length of die block in mm > 100.0; and Length of die block in mm ≤ 200.0; and Width of die block in mm > 100.0; and Width of die block in mm ≤ 200.0 and Tolerance on part in mm ≤ 0.005 Direction of feed of strip to the die-set = Parallel	Place die in the four pillar die-set with pillar having diameter of bush in mm = 24.0; and Bolster dimension in mm = 34.0; and Length of die-set in mm = 280.0 Width of die-set in mm = 250.0 height of die-set in mm = 26.0
9	Die area > 15,000 $mm^{2;}$ and Die area ≤ 25,000 mm^2	Use four Allen bolts of size M8; and Four dowels of diameter in mm = 8.0
10	Sheet thickness in mm > 0.5 and; Sheet thickness in mm ≤ 1.0 and; Diameter/dimension of outer part feature in mm ≤ 25.0	Select knockout bar without head M2 HSS; and Diameter of knockout bar in mm = 3.0; and Length of knockout bar in mm = 55.0

3.2 Subsystem CDCOMP

The subsystem labeled as CDCOMP is developed for selection of type and size of components of compound die. The proposed system consists of eight modules. A sample of production rules incorporated in the proposed system is given in Table 2. Execution of the system is shown in Fig. 5 (Kashid and Kumar 2014b). The first module, namely, DBLOCK is developed for selection of proper size of die block. Initially, the module takes required input data from the data files FE.DAT (generated during execution of FE system) and PD.DAT. The module also takes required data in form of size of strip automatically from the data file labeled as STSEL.DAT generated during execution of previous subsystem. Thereafter user has to select type of die material through GUI. Finally, module displays the size of die block and it is stored automatically in data file, namely, DBLOCK.DAT. The next module namely DGAGE has been constructed for selection of proper size of die gages and distance between gages. Initially, user has to select shape of die hole contour (e.g., smooth/inside corners/sharp inside corners). The module is designed to take required input from data file labeled as FE.DAT and PD.DAT. Finally, the module displays the size of die gages and distance between two gages. This output is stored automatically in a data file, namely, DGAGE.DAT. The module STRP is developed for selection of stripper (Kashid et al. 2015). It takes required inputs from data files generated during execution of previous modules. The outputs in form size of stripper and stripping force are stored automatically in an output data file namely STRP.DAT. Similarly, other modules, namely, STSPR, CDCPUN, DISET, and FSTN are developed, respectively, for selection of stripper springs, type and size of punches, type and size of die-set, and number and size of fasteners (Kashid and Kumar 2014a). All these modules take required inputs from output

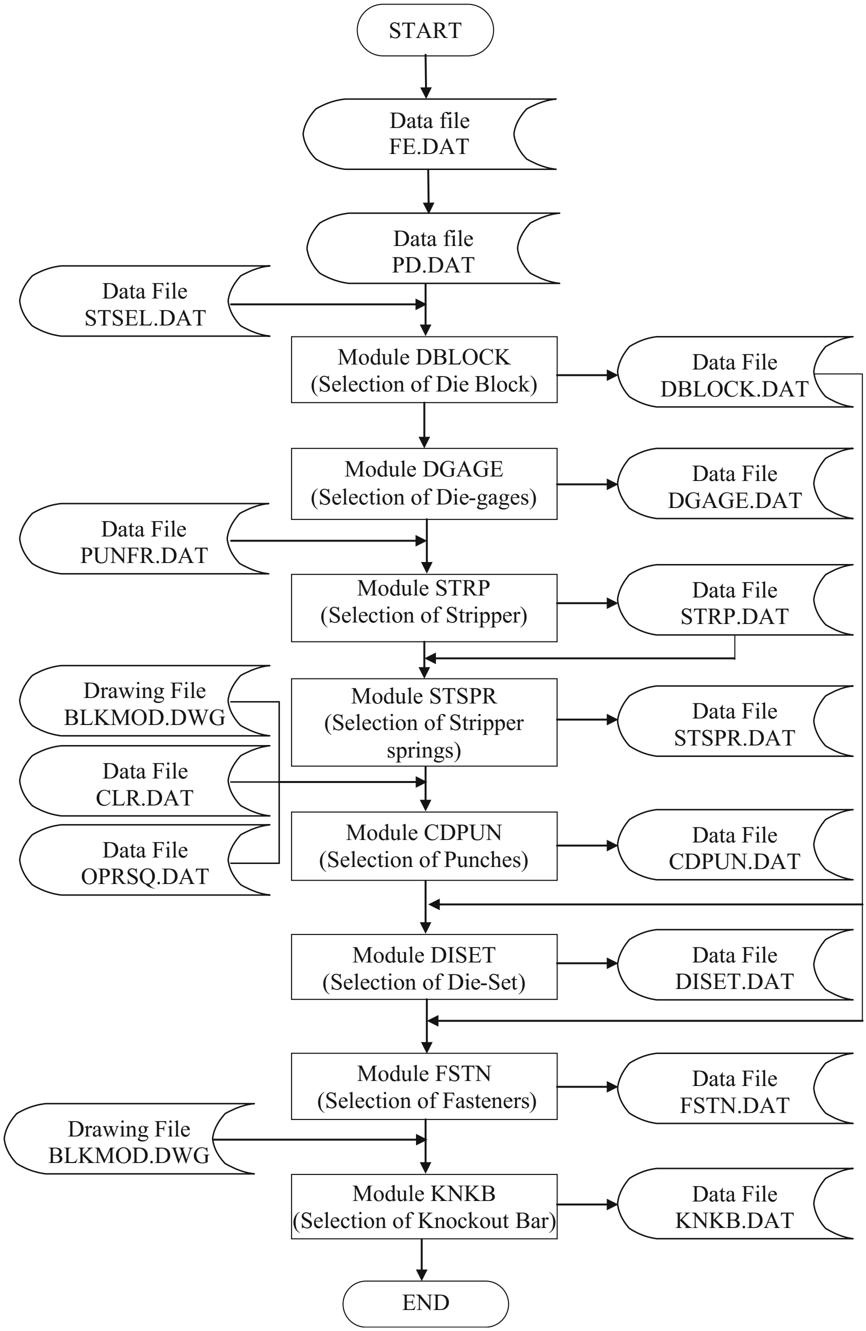


Fig. 5 Execution of the subsystem CDCOMP

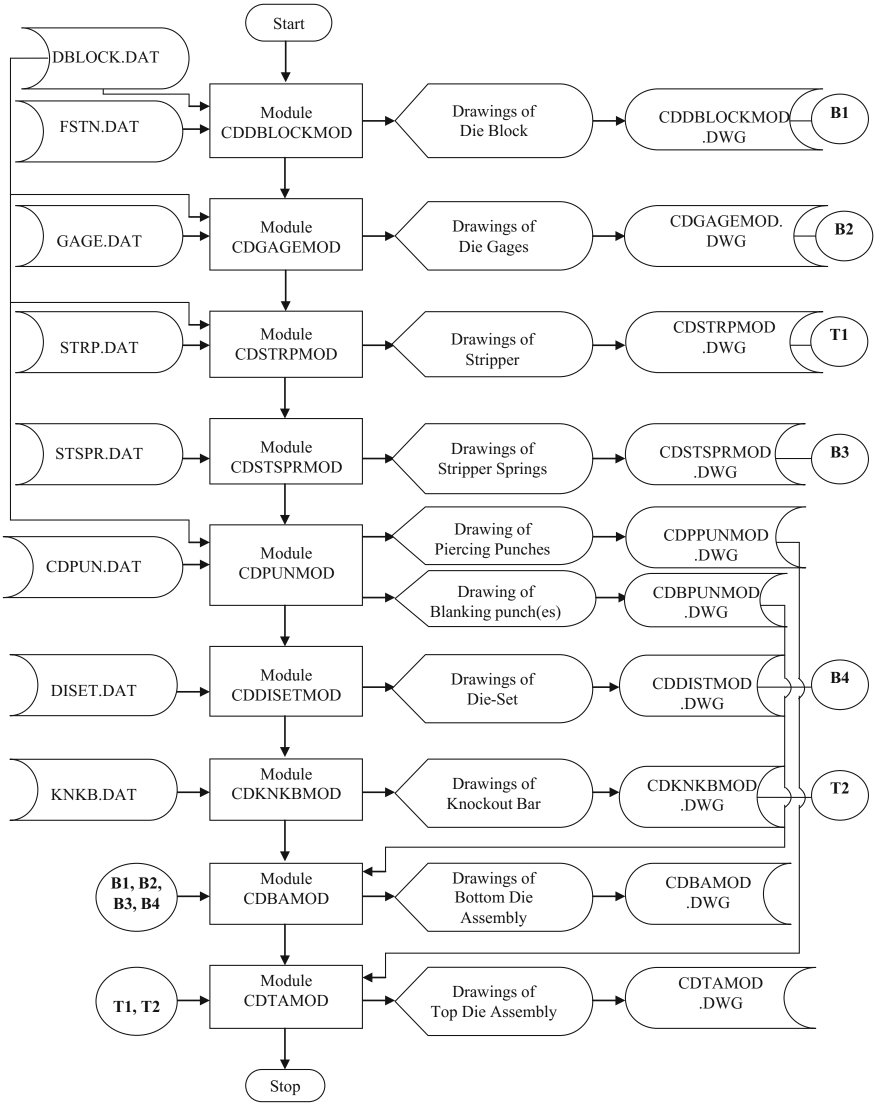


Fig. 6 Execution of subsystem AUTOMODCD

data files of previous modules and store their outputs automatically in respective individual data files.

3.3 Subsystem AUTOMODCD

The subsystem labeled as AUTOMODCD has been developed for automatic modeling of die components and die assembly. The system consists of eight modules, namely, CDDBLOCKMOD, CDGAGEMOD, CDSTRPMOD, CDSTSPRMOD, CDPUNMOD, CDDISETMOD, CDKNKBMOD, CDBAMOD, and CDTAMOD developed, respectively, for modeling of die block, die gages, stripper, stripper springs, punches, die-set, knockout bar, bottom die assembly, and top die assembly of compound die. The execution of proposed subsystem is shown in Fig. 6 (Kashid and Kumar 2016). The system is designed in such a way that the required inputs in form of size of die components are taken automatically from data files generated during execution of previous modules of subsystem CDCOMP. Modules generate 2-D and 3-D drawings of all major die components, bottom die assembly, and top die assembly of compound die in AutoCAD.

4 Validation of the Proposed System

The proposed system ESIDCD has been tested successfully for different sheet metal parts taken from stamping industries. A sample run of the system for one sheet metal part (Fig. 7) of stamping industry namely M/s D. D. Engineering Pvt. Ltd., Pune, India is depicted in Figs. 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29 and 30. Recommendations obtained by the proposed system were found very similar to those actually used in the sheet metal industry for the example part. Usually an experienced die designer (having more than 15 years of experience) of a stamping industry spends around three working days (considering 8 h shift per day) for process planning, selection of size of die components, and die drafting for the said example part. The stamping industry pays approximately Indian Rs. 15,000 ($250 approx.) to this die designer for this task. The proposed system performs the task of die design in less than an hour without the assistance of any experienced die designer. Even a fresh engineer can easily operate the system. The proposed system is capable to handle all types of sheet metal parts produced on compound die.

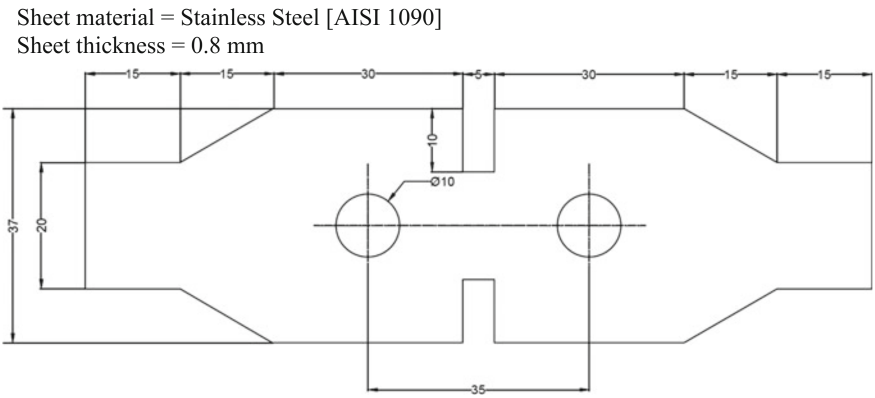


Fig. 7 Example part (all dimensions are in mm) (M/s D. D. Engineering Pvt. Ltd., Pune, India)

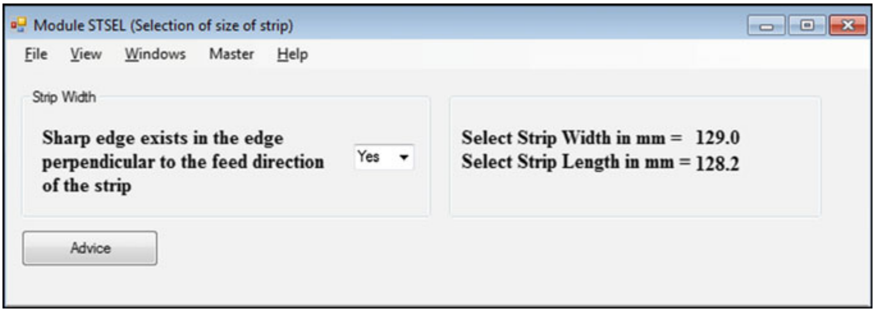


Fig. 8 Output of STSEL module for example part

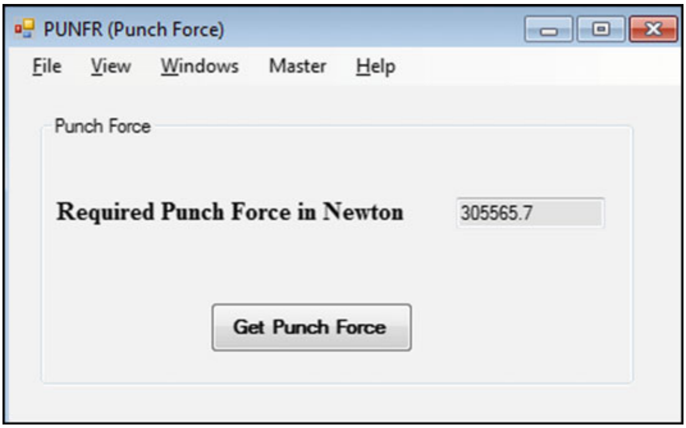


Fig. 9 Output of PUNFR module for example part

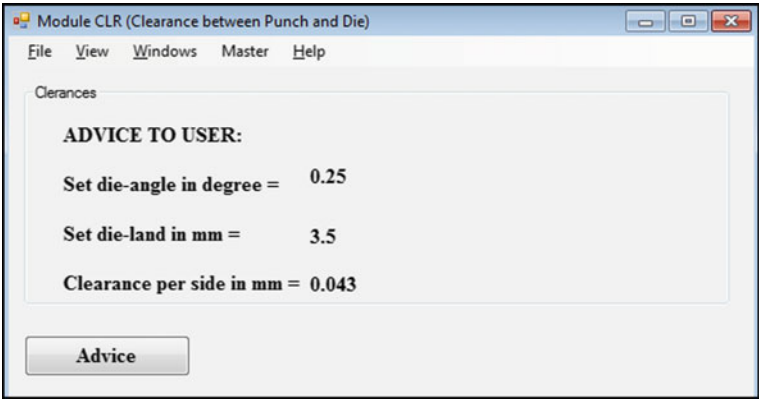


Fig. 10 Output of CLR module for example part

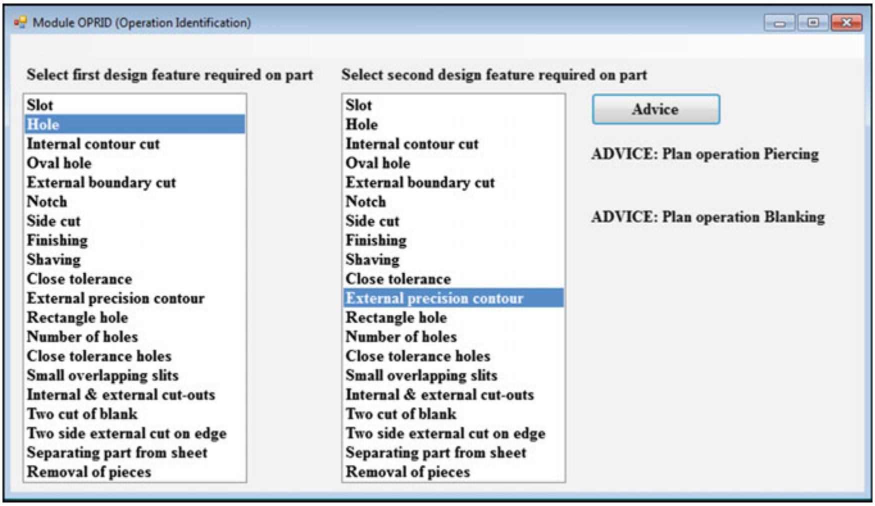


Fig. 11 Output of OPRID module for example part

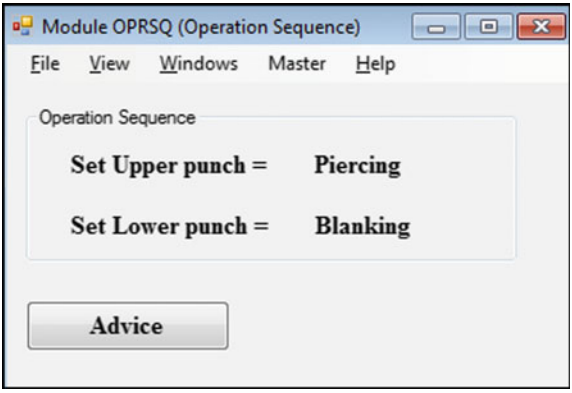


Fig. 12 Output of OPRSQ module for example part

Fig. 13 Output of DBLOCK module for example part

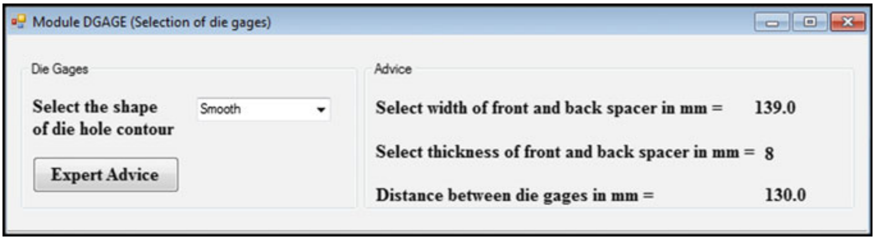


Fig. 14 Output of DGAGE module for example part

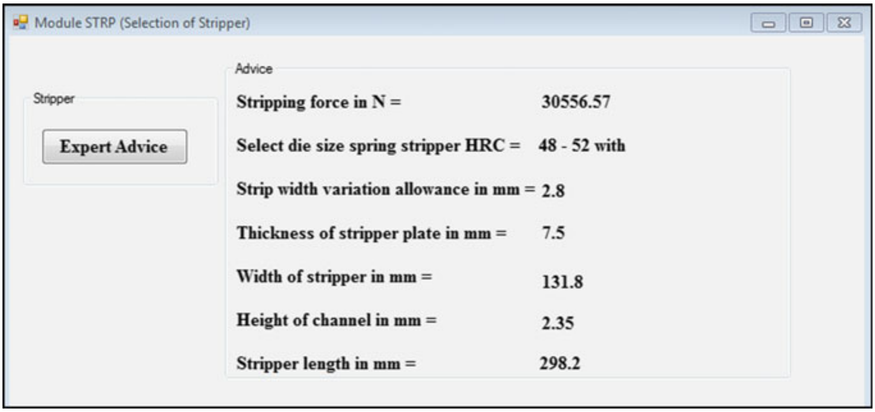


Fig. 15 Output of STRP module for example part

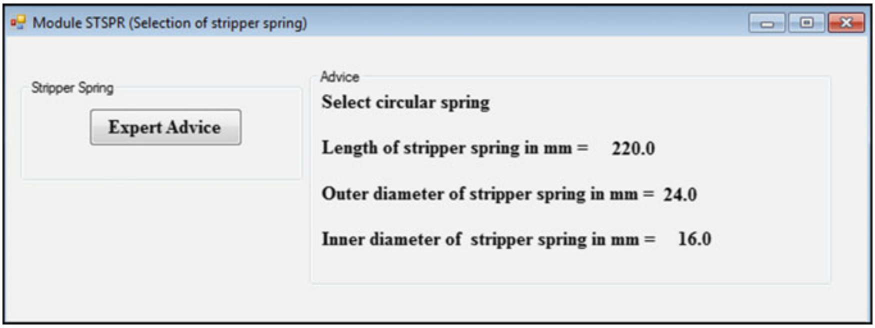


Fig. 16 Output of STSPR module for example part

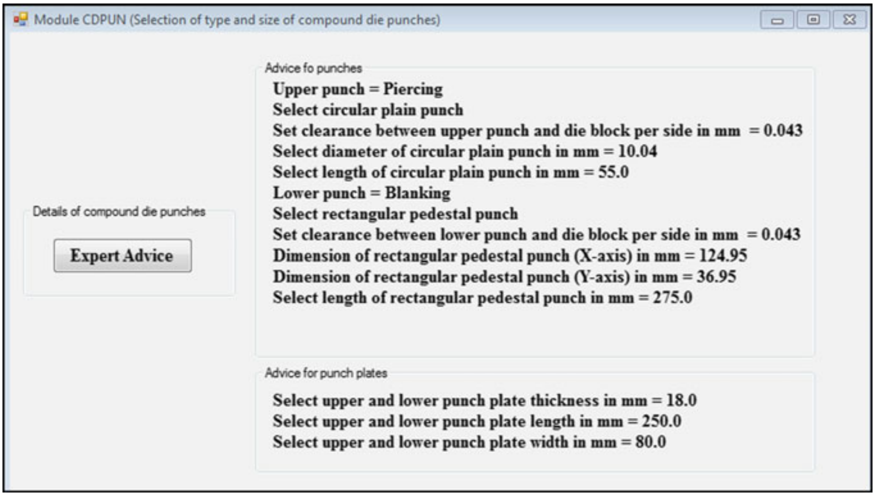


Fig. 17 Output of CDPUN module for example part

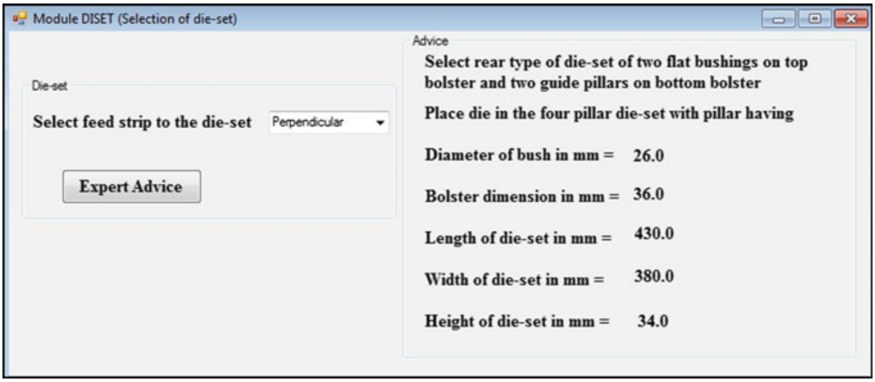


Fig. 18 Output of DISET module for example part

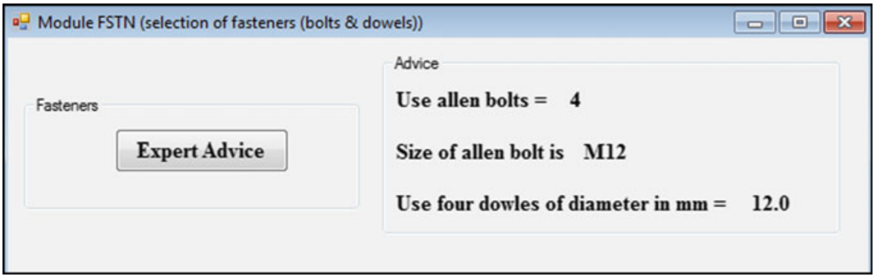


Fig. 19 Output of FSTN module for example part

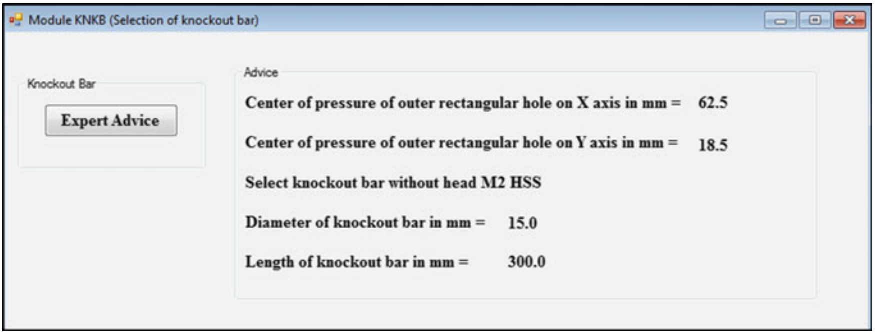


Fig. 20 Output of KNKB module for example part

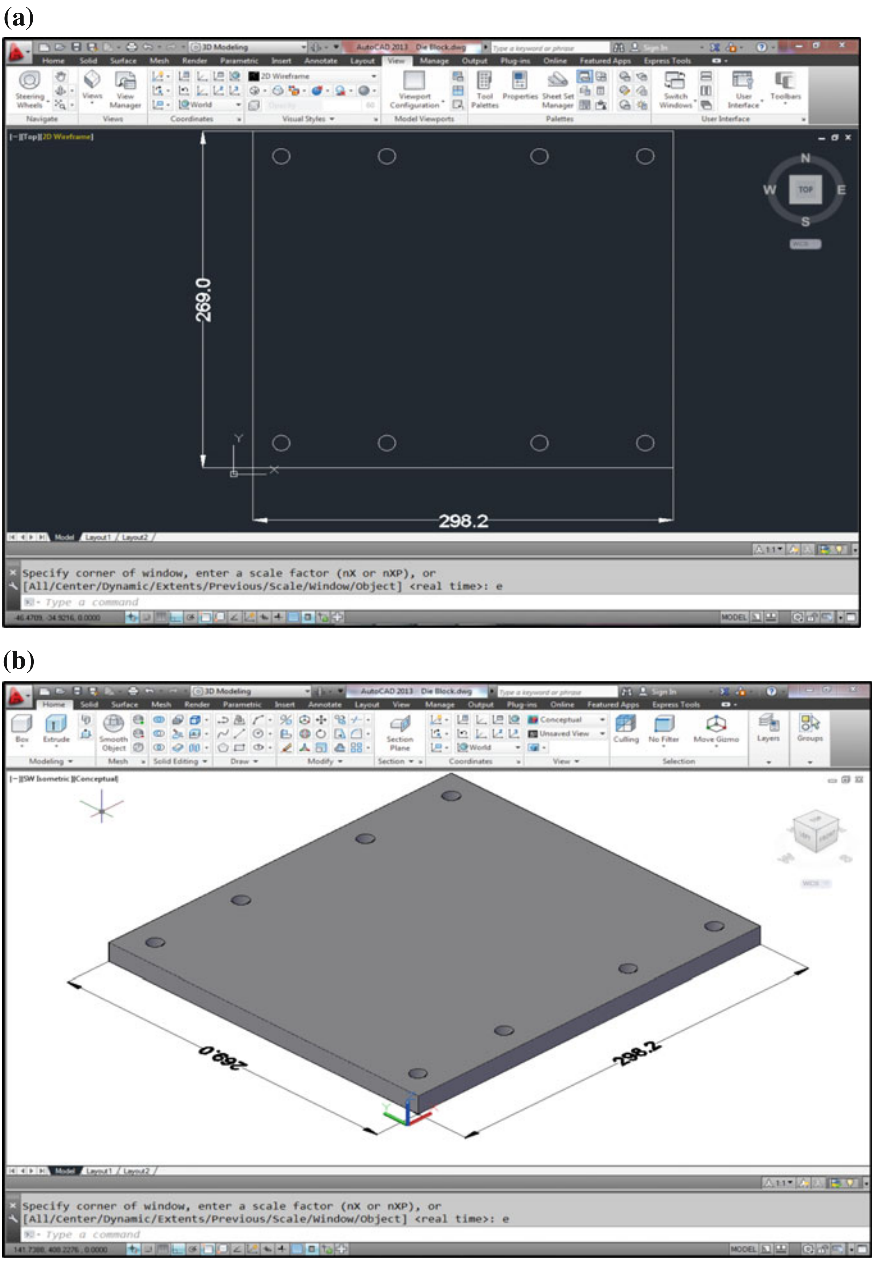
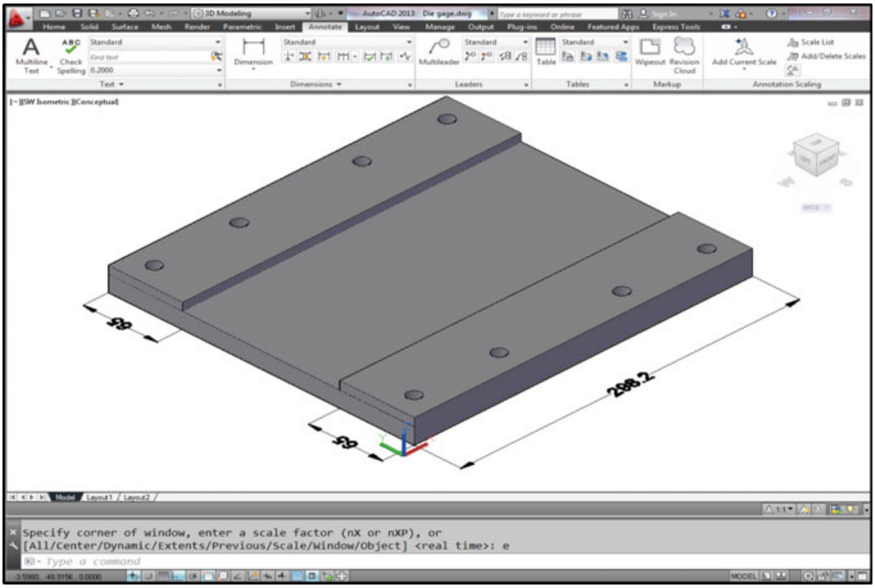


Fig. 21 2-D and 3-D views of die block for example part **a** 2-D view of die block **b** 3-D view of die block

(a)



(b)

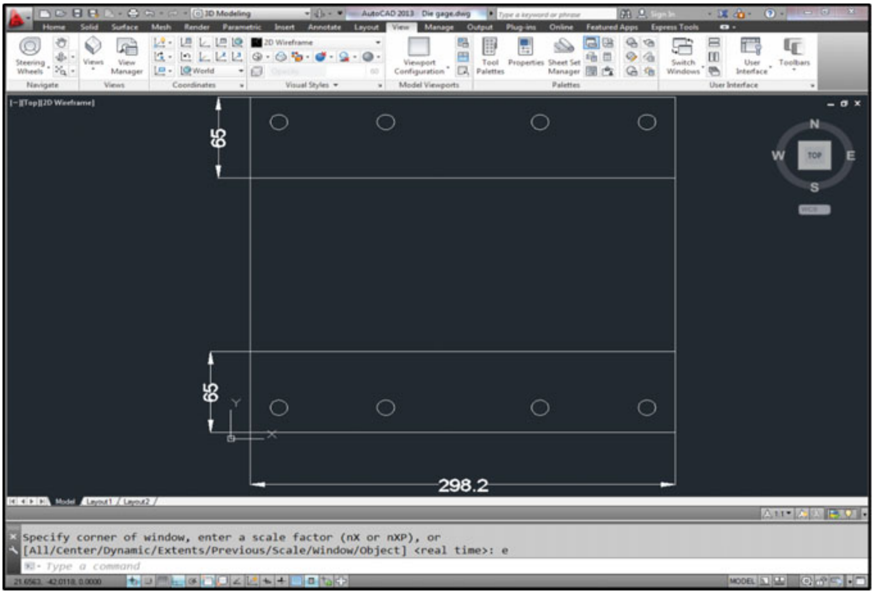
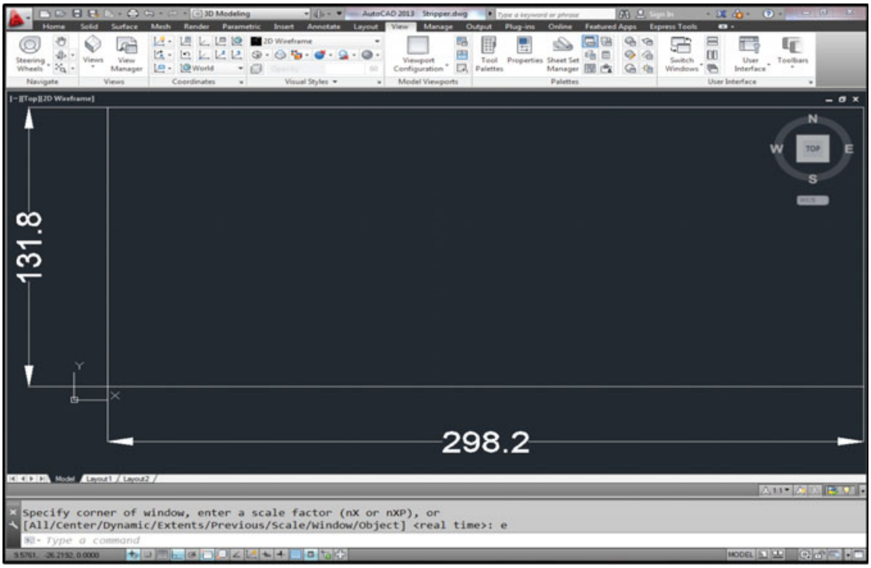


Fig. 22 2-D and 3-D views of die gages for example part **a** 2-D view of die gages **b** 3-D view of die gages

(a)



(b)

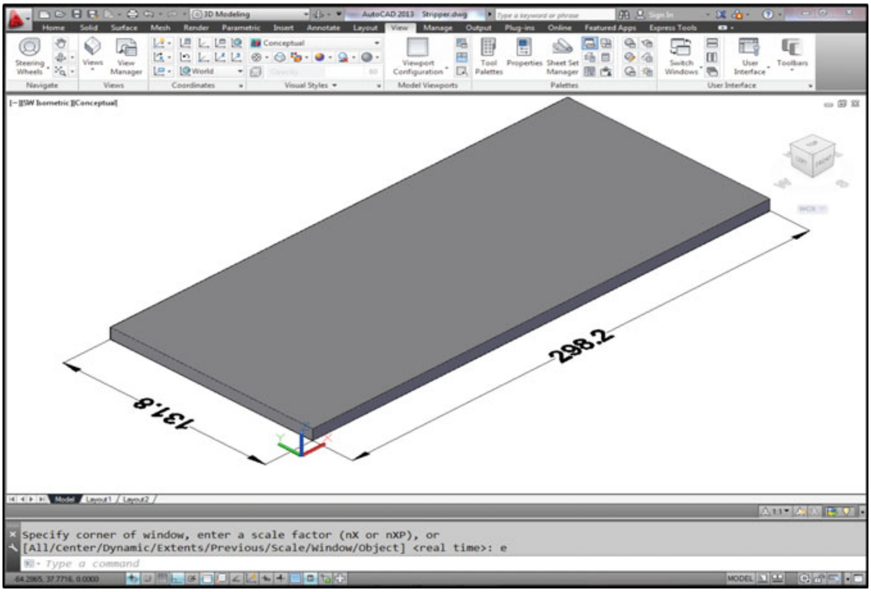
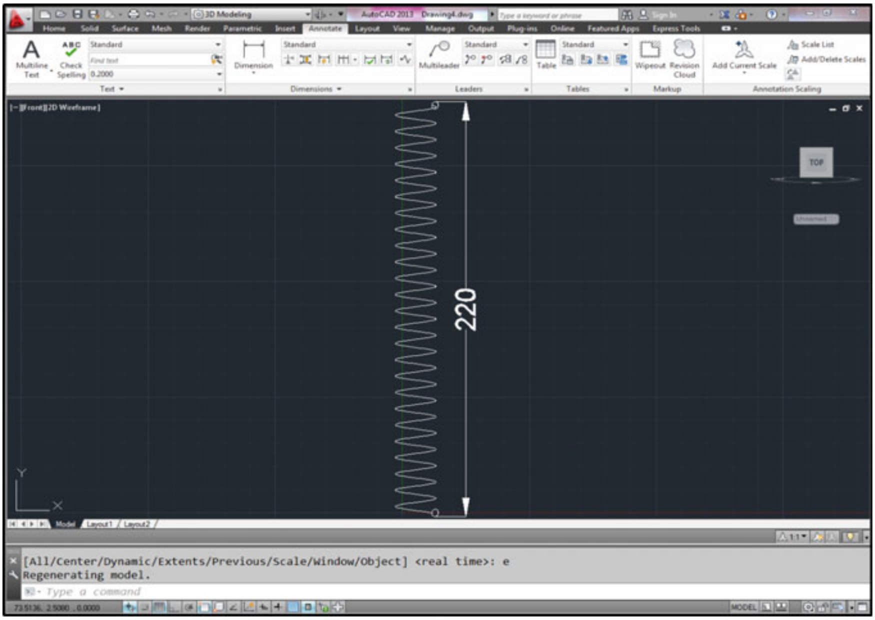


Fig. 23 2-D and 3-D views of stripper for example part **a** 2-D view of stripper **b** 3-D view of stripper

(a)



(b)

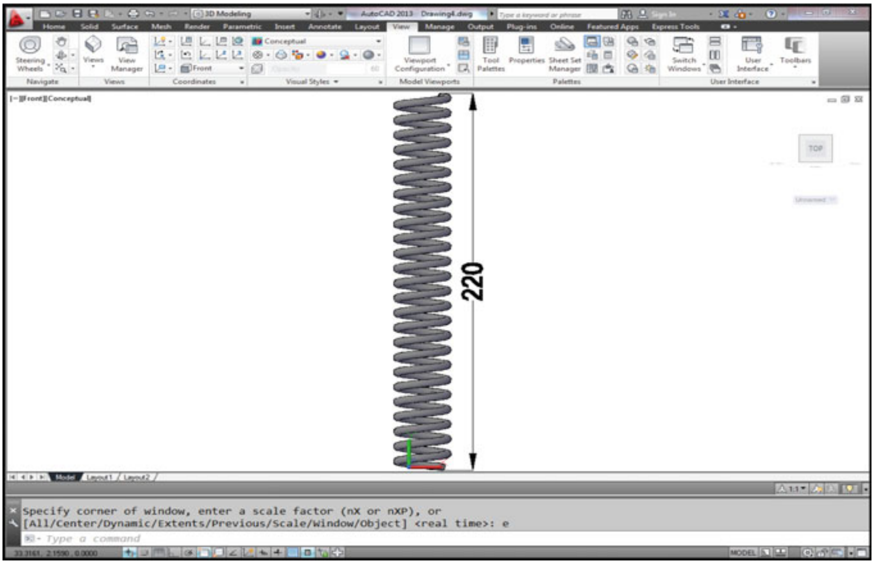
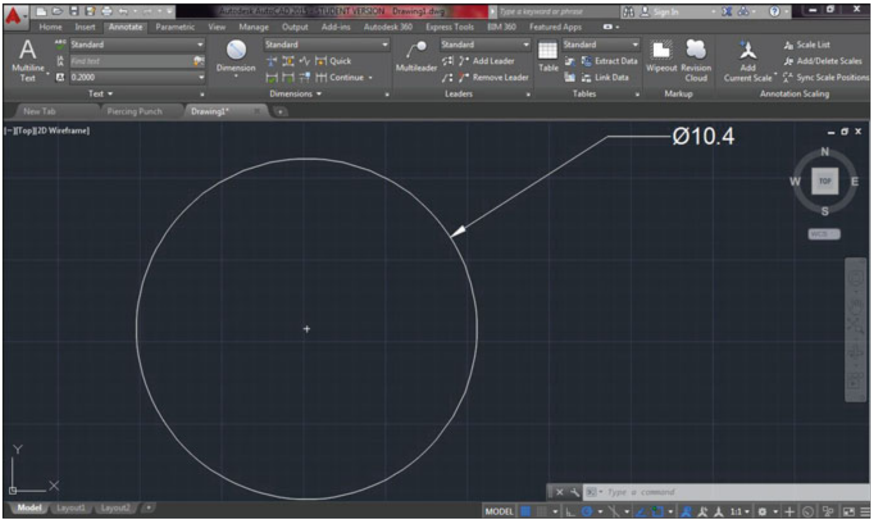


Fig. 24 2-D and 3-D views of stripper spring for example part **a** 2-D view of stripper spring **b** 3-D view of stripper spring

(a)



(b)

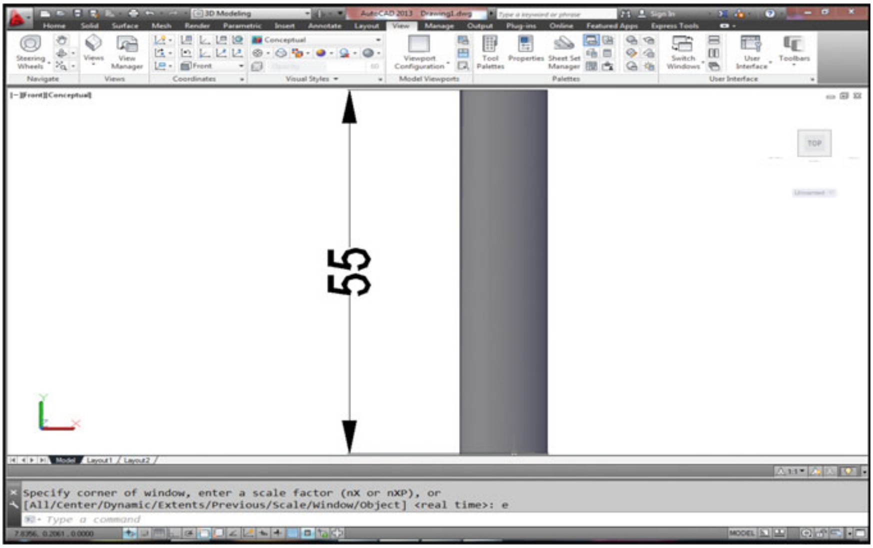


Fig. 25 2-D and 3-D views of piercing punch for example part **a** 2-D view of piercing punch **b** 3-D view of piercing punch

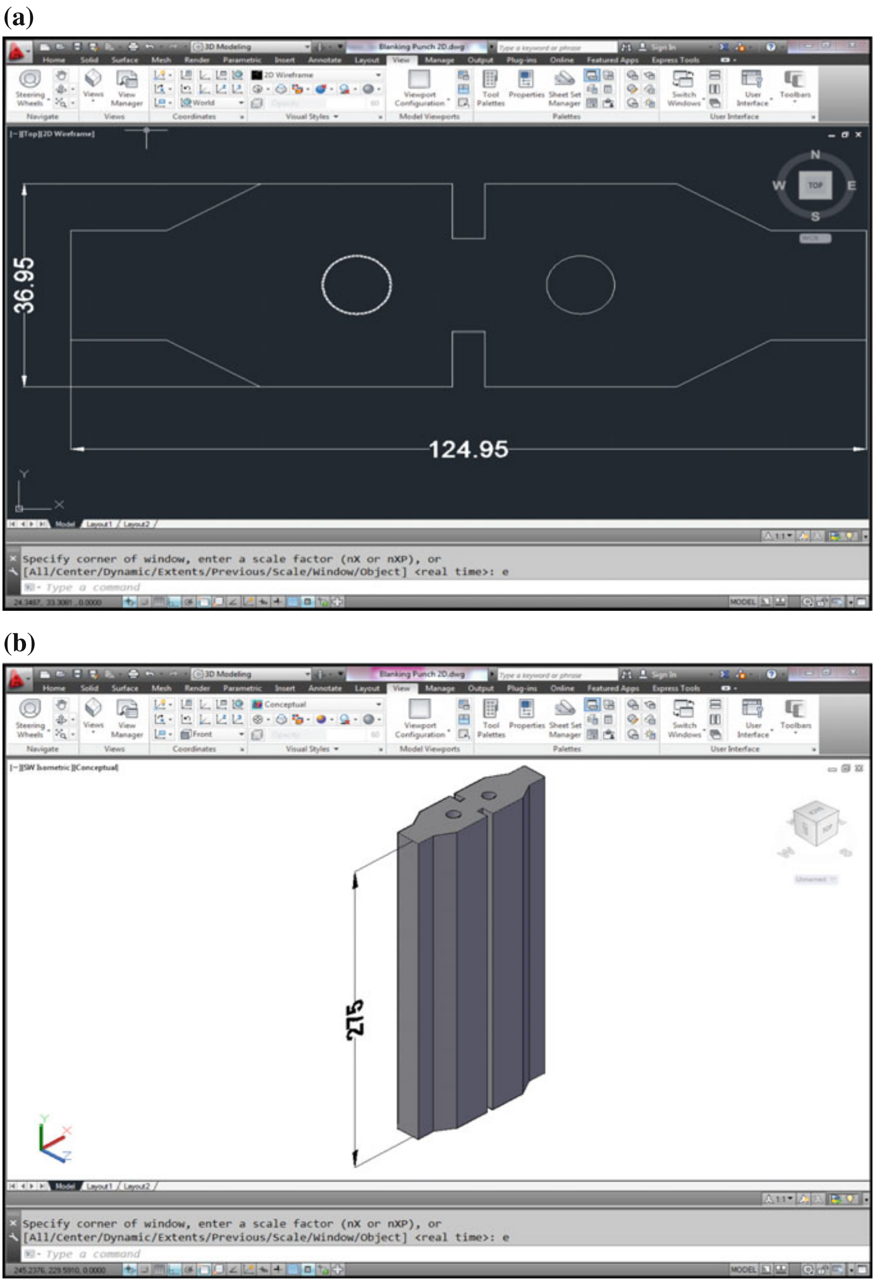
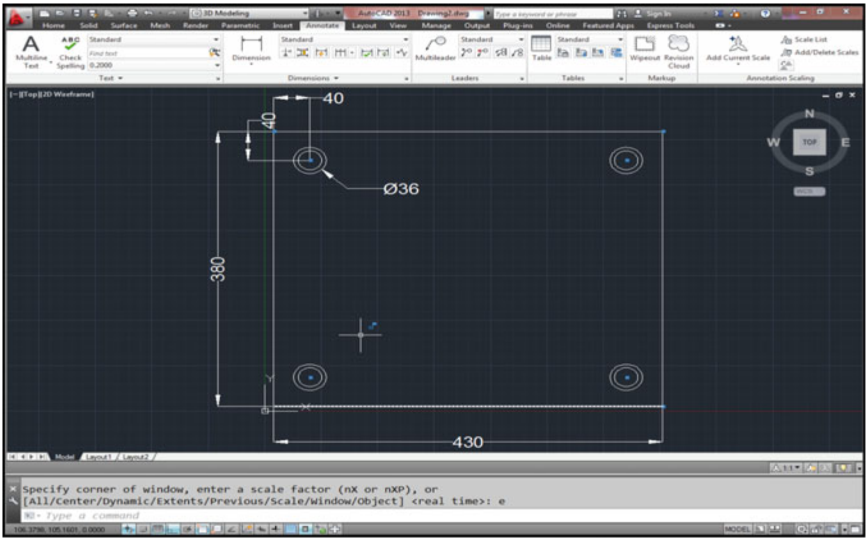


Fig. 26 2-D and 3-D views of piercing punch for example part **a** 2-D view of blanking punch **b** 3-D view of blanking punch

(a)



(b)

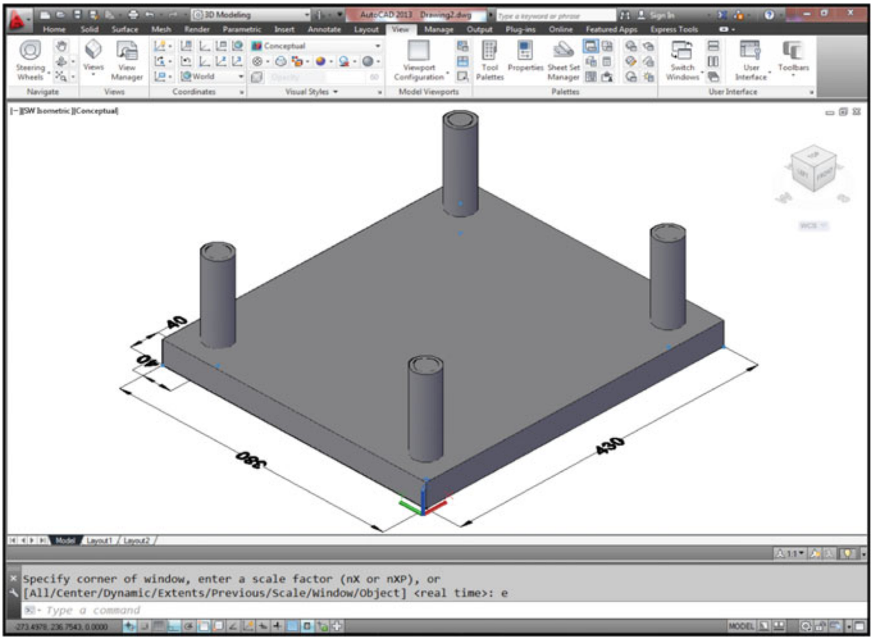
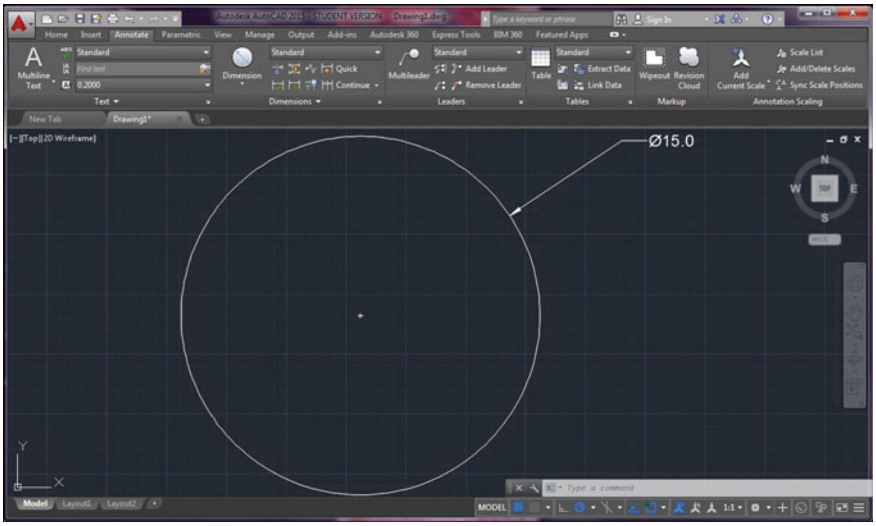


Fig. 27 2-D and 3-D views of die-set for example part **a** 2-D view of die-set **b** 3-D view of die-set

(a)



(b)

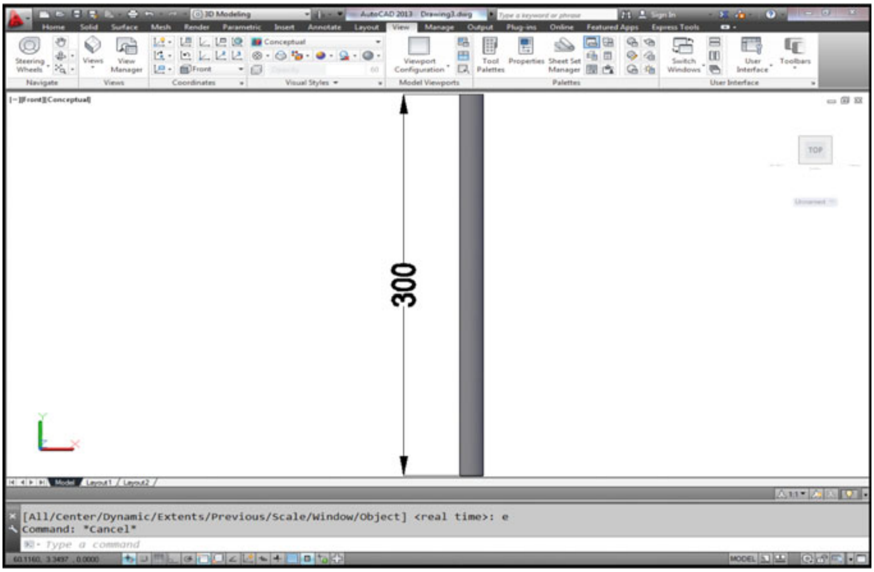


Fig. 28 2-D and 3-D views of knockout bar for example part **a** 2-D view of knockout bar **b** 3-D view of knockout bar

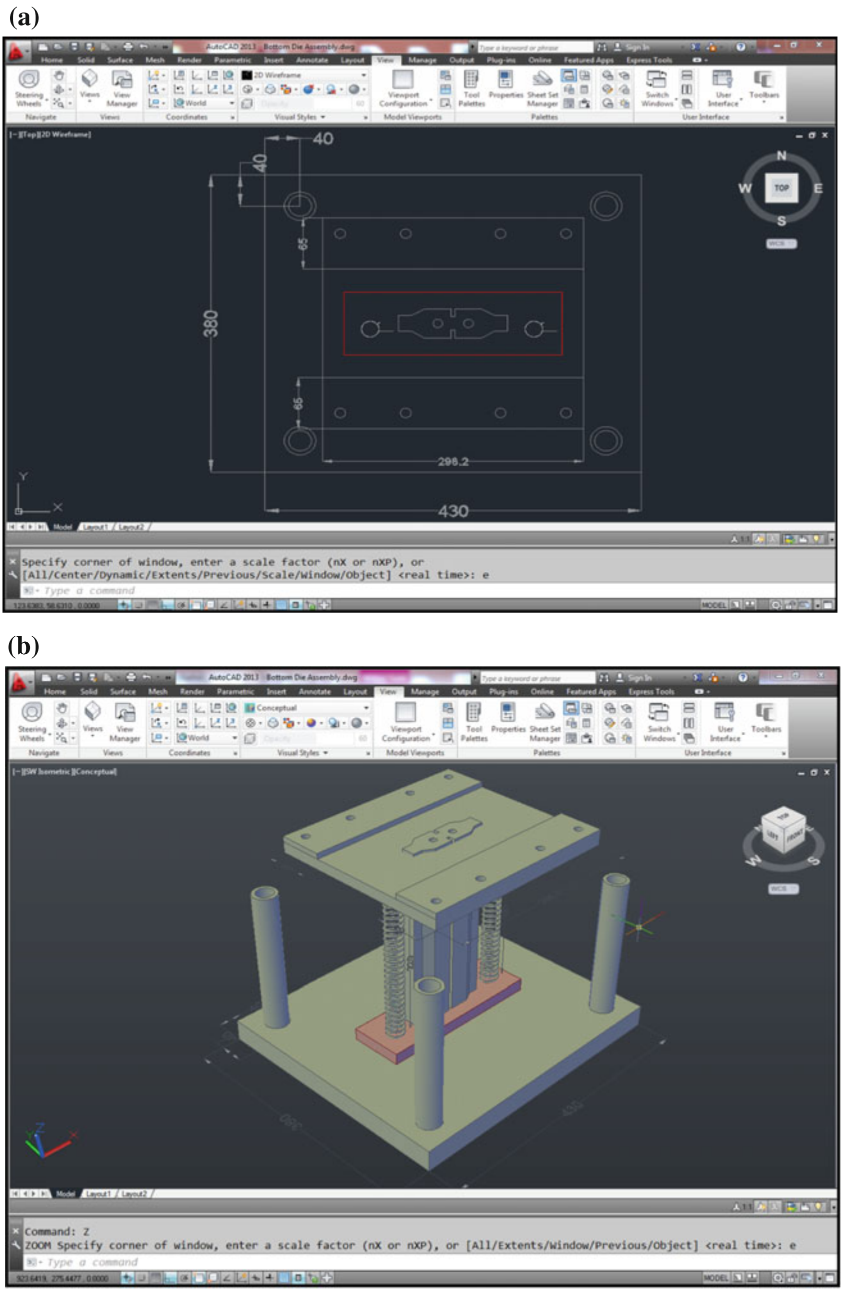
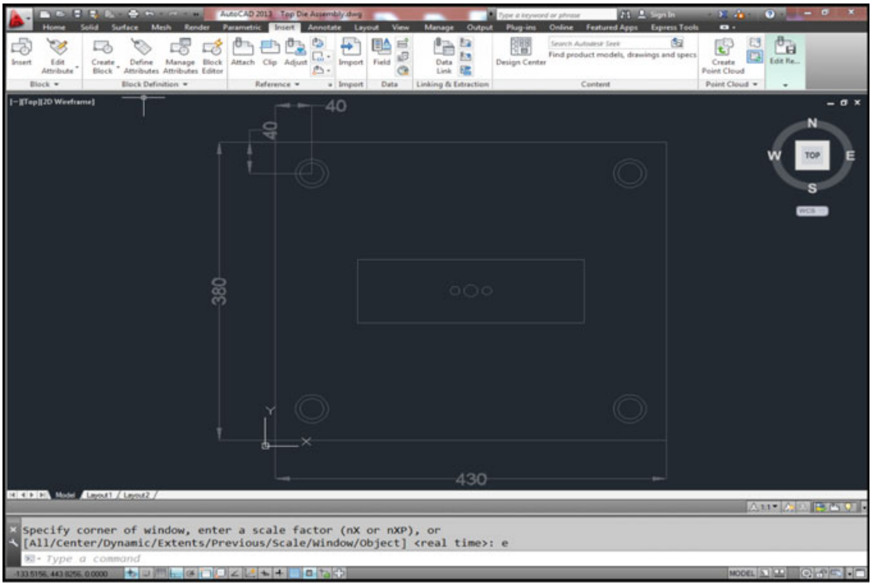


Fig. 29 2-D and 3-D drawings of *bottom* die assembly for example part **a** 2-D drawing of *bottom* die assembly **b** 3-D drawing of *bottom* die assembly

(a)



(b)

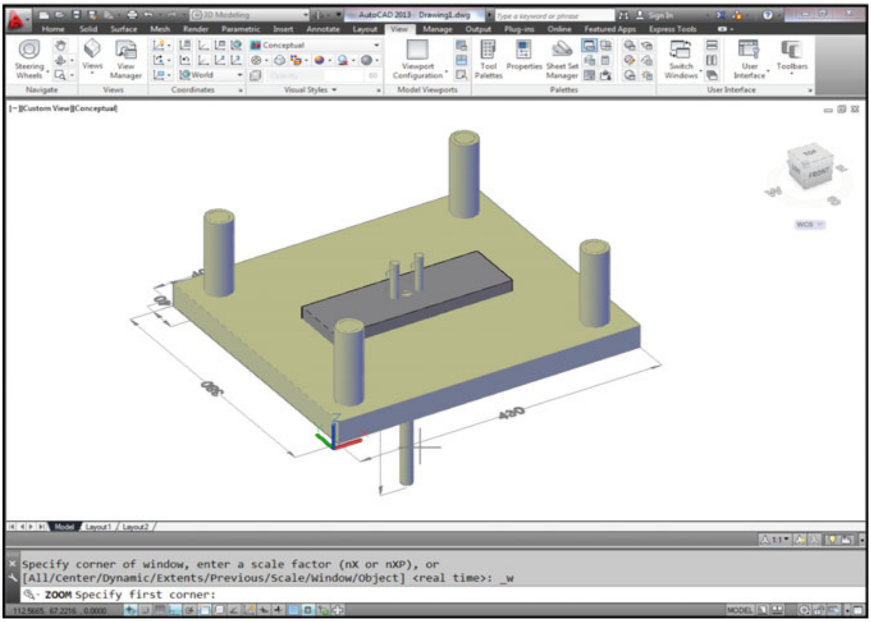


Fig. 30 2-D and 3-D drawings of *top* die assembly for example part **a** 2-D drawing of *top* die assembly **b** 3-D drawing of *top* die assembly

5 Conclusion

This chapter describes an expert system developed for automatic design of compound dies. The overall system has been organized into various subsystems and modules. The system selects various process planning parameters such as size of strip, punch force, clearance between punch and die, sheet metal operations, and proper sequence of operations. After completion of process planning, the systems selects type and size of various die components including die block, die gages, stripper, stripper springs, punches, punch plate, die-set, fasteners, and knockout bar. Finally, the proposed system generates 2-D and 3-D drawings of all major die components, and bottom and top die assembly of compound die in AutoCAD software. The developed system has been tested successfully on various types of sheet metal parts taken from stamping industries. The system is integrated and parametric in nature. The proposed system can be modified depending upon the capabilities of a specific shop floor. The low-cost implementation of the proposed system makes it affordable even for small scale stamping industries.

Although the proposed expert system deals with compound dies only, yet it can be extended further to automate design process of combination dies also.

Acknowledgments Authors thank all domain experts for providing expertise in the development of proposed expert system. Authors also acknowledge the sanction of the project on "Automation of design of compound dies for sheet metal industries" (File No. SB/S3/MMER/0061/2013) by the Science and Engineering Research Board (SERB), Department of Science and Technology (DST), Government of India, New Delhi, India.

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Prediction of Life of Compound Die Using Artificial Neural Network

Sachin Salunkhe, Shailendra Kumar and Hussein M.A. Hussein

1 Introduction

Compound dies are widely used in sheet metal industries for manufacturing of pierced blanks with good accuracy. Current sheet metal industries require compound dies of good quality with long life to carry out sheet metal operations economically and with high productivity without causing any surface or internal defects on sheet metal parts. Therefore, prediction of life of compound die is an important activity in sheet metal industries. Die life is usually defined as the number of parts produced by a die before its failure. The life of compound die depends mainly on its active components including die block, punches (piercing and blanking), and stripper. To predict the die's life, punch force and stripping force need to be calculated. Punch force required for stamping depends on sheet's thickness, shear strength of sheet material, and area of design feature of sheet metal part.

During past 10–15 years, various artificial intelligence (AI) techniques have been applied for solving complicated problems in almost all areas of engineering. Knowledge-based system/expert system and artificial neural network (ANN) are the most powerful tools of artificial intelligence (AI) for solving engineering problems which are complex, time-consuming and highly experience-based. ANN is inspired

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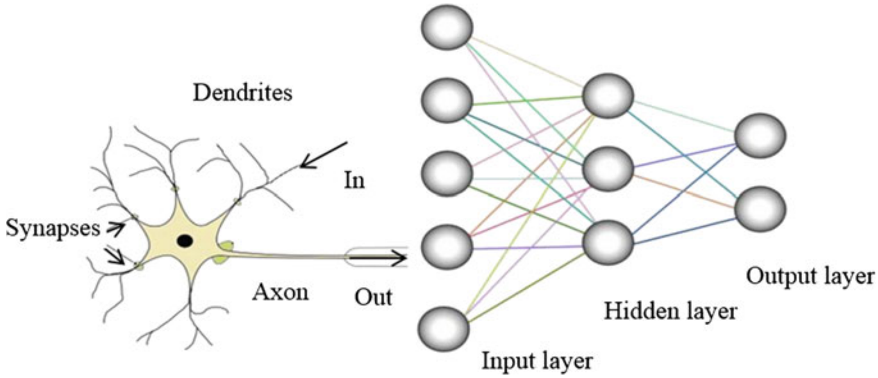

Fig. 1 A schematic diagram of ANN inspired by biological nervous system (Kriesel 2007)

both by human biological nervous systems and mathematical theories of learning, information processing, and control as shown in Fig. 1 (Tabatabaei et al. 2011).

Figure 2 shows the structure of ANN. $X_1, X_2, X_3, \ldots, X_i$ are the inputs with respect to $W_1, W_2, W_3, \ldots, W_i$ as the weights of the input functions. All the input data (input function and weight function) are represented by linear combination of the output.

$$\mathrm{Net}_{(j)} = \sum_i X_i W_i \tag{1}$$

where, 'j' is the communication link between neuron and computation neuron node is 'i'. ANNs are nonlinear function processing structures in which the elements called as neurons process the information. Signals are transmitted from input to output which is called connecting links. The connecting links are associated to weight, which is multiplied along with the incoming signal, i.e., net input for any

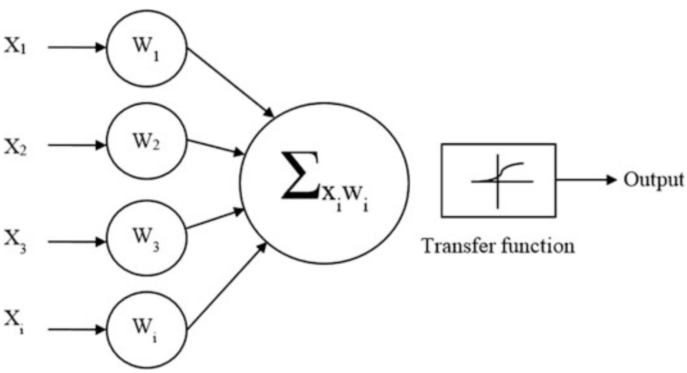

Fig. 2 Artificial neural network (ANN) (Kriesel 2007)

typical neural network. Recently, researchers have applied efforts to use ANN technique for manufacturability analysis, process planning, die design, prediction of finite element simulation results, etc., in sheet metal work. Sheet metal product development and design of dies usually involve several design parameters. A subtle change of any parameter constitutes a new design scenario and new simulations are needed to explore its behaviors and performance. It is not practical to find the optimal solution through one-by-one simulation. To address this issue, ANN technique along with finite element analysis (FEA) can be used effectively to find out the highly nonlinear relationship between the designs parameters in sheet metal product development and die design.

Applications of ANN technique to sheet metal work have given a new dimension in the late 1990 and early 1995s (Kim and Kim 2000). ANN technique to sheet metal involves prediction of process planning parameters; prediction of FEM results, etc. Worldwide researchers used ANN technique for development of various systems to ease the activities related to sheet metal work (Kashid and Kumar 2012). Lin and Chang (1995) proposed neural network (NN)-based expert system for sheet metal bending. They divided learning model into two categories according to their problem attributes—digital attributes and conditional attributes. Roy (1996) demonstrated sheet metal bending with the help of ANN. ANN is used to predict the forces required for a number of bending experiments and to achieve a zero spring-back angle. Lin and Chang (1996) used fuzzy set theory, ANN and expert system to the design details of the uncertainty portion of progressive die design. Backpropagation algorithm is used for training. Ruffini and Cao (1998) proposed ANN and FEM to minimize spring-back in a cannel forming process. Multi-layer feed-forward NN with backpropagation algorithm is used. Geiger et al. (1998) developed ANN model for cost estimation of sheet metal parts. Manabe et al. (1998) proposed combination of ANN and the elementary plasticity theory for identification of material properties and lubrication condition in the deep-drawing process. Forcellese et al. (1998) applied ANN technique to air-bending process. Wu et al. (1999) presented combination of ANN and machine learning methods for surface defect (wrinkling and buckling) investigation in sheet metal forming. Wadi and Balendra (1999) proposed ANN model for prediction of blanking process and blanking parameters by analyzing acoustic emission (AE) and force/displacement waves. Ivezic et al. (1999) applied ANN technique to inverse modeling of material deformation. They used gradient descent and backpropagation algorithm. Kim and Kim (2000) proposed ANN and FEM for metal forming process. ANN is used to reduce the number of finite element simulation for designing die of forging products. Three-layer NN and backpropagation algorithm is used to train. Inamdar et al. (2000a) developed ANN system for prediction of spring-back in air vee bending of metallic sheets. Backpropagation algorithm is used. Multi-layer perceptron (MLP) NN is developed and used for the prediction of spring-back. Further they (2000b) considered two-layers with a sigmoid activation function as well 5 input nodes, 10 hidden nodes, and 2 output nodes. Cheng and Lin (2000) used ANN to predict bending angle of sheet metal formed by laser. They used three supervised neural networks to estimate bending angles formed by a laser. Drugos et al. (2000)

applied NN technique for prediction of laser sheet metal bending. They used backpropagation algorithm for learning and multi-layer perceptron, and nonlinear sigmoid function as an activation function. Wang et al. (2000) introduced ANN to predict and avoid surface failures, such as wrinkling in sheet metal forming.

Hambli (2002, 2005) used combination of ANN and FEM for prediction of burr height formation in blanking process. They used backpropagation algorithm for training purpose and predicted burr height of blanked parts versus tool wear state and punch-die clearance. Further they used multi-layer perceptrons (MLP) architecture and sigmoid (logistic) as an activation function. Further, FEM and ANN methods are also used to predict the optimum punch-die clearance during sheet metal blanking processes. ANN technique is used for mapping between inputs and output data (FEM simulation data). Backpropagation algorithm is used for training purpose. Frayman et al. (2002) developed ANN for inverse model of a sheet forming process, and compare its performance with that of a linear model. Luo et al. (2003) developed ANN and analytic method to overcome the defects in deep drawing process. Hambli and Guerin (2003) used ANN for prediction of optimum punch-die clearance in sheet metal blanking process with the help of finite element method (FEM). They used backpropagation algorithm for training purpose, multi-layer perceptrons (MLP) architecture and sigmoid (logistic) as an activation function. Slomp and Klingenberg (2004) proposed ANN for detection of punching/blanking characteristics from the force–displacement graph. Pathak et al. (2005, 2008) studied prediction responses of the sheet metal bending process using ANN. Forty-four cases are analyzed using FEM to train NN. Further, they used ANN for prediction of geometrical instabilities like wrinkling and necking in deep drawing. Zhao and Wang (2005) presented a feed-forward NN model based on the LM algorithm (put forward by Levenberg and Marquardt) to realize real-time identification of material properties and friction coefficient for deep drawing of an axisymmetric work piece. Singh and Kumar (2005) used ANN to predict the thickness along a cup wall in hydro-mechanical deep drawing.

Liu et al. (2007) proposed a technique based on ANN and genetic algorithm (GA) to solve the problem of spring-back in sheet metal forming. They investigated spring-back of the typical U-shaped bending. Further, the study on the relation of spring-back and various process parameters is also carried out on the model of spring-back. They used backpropagation algorithm. Klingenberg and Boer (2008) presented a review and proposal for condition-based maintenance (CBM) in blanking of sheet metal. Bozdemir and Golcu (2008) used ANN to determine the effects of material, bending angle, and ratio of bend angle to sheet thickness on spring-back angle. Ruan et al. (2008) used backpropagation, NN, and GA to predict spring-back of complex sheet metal forming parts. Kurtaran (2008) compared experimental (data table approach), empirical, ANN, and Response Surface (RS) approaches for bend allowance calculation in air bending. Sivasankaran et al. (2009) developed ANN model for predicting and avoiding surface failure such as wrinkling of sheet metals. Kazan et al. (2009) developed prediction model of spring-back in wipe-bending process of sheet metal using ANN approach. Aguir et al. (2009) presented an inverse strategy coupled with an ANN model for identification of anisotropic parameters of cylindrical cup deep drawing. ANN model is trained by finite element simulations. Djavanroodi et al. (2010) investigated the possibility of using FEM together with ANN for the analysis of fine blanking process. Li et al. (2010) used ANN and GA for optimization of sheet metal deep drawing parameters with variable blank holder force. Hanazono et al. (2010) reported to use ANN to determine parameters of slide-bending formation of metallic sheet. Fu et al. (2010) developed three-layer back propagation NN to predict punch radius based on the results of air-bending experiments of sheet metal. Liu and Yi (2010) used combination method of test design, FEM and NN modeling for prediction of spring-back of automobile ceiling. Deng and Zhang (2010) tried to build a function relationship between the spring-back and the craft parameters with ANN. Du et al. (2010) proposed Double Chains Quantum Genetic Algorithm (DCQGA) and backpropagation NN for prediction of bending angle in the laser bending process of sheet metal.

Gisario et al. (2011) investigated spring-back control in the bending process of aluminum sheets by hybrid forming process. Ren et al. (2011) used backpropagation NN to establish the intelligent prediction model of pipe forming process parameters, and the main process parameters including bending moment. Zhang (2011) used FEM simulation and ANN to optimize the blank holder force (BHF) for drawing of automobile fuel tank. Singh et al. (2011) applied error back propagation NN in collaboration with GA to investigate the role of die radius, punch radius, friction coefficients and drawing ratios for axisymmetric deep drawing process. Choi et al. (2011) proposed a channel-type indirect blank holder to develop a high-strength center pillar in form-type hot stamping to reduce severe wrinkling at the flange. Nasrollahi and Arezoo (2012) investigated the influence of process variables such as hole type, number of holes, the ratio of hole width to sheet width, die radius and pad force on spring-back in sheet metal components using FEM and ANN. Hussaini et al. (2014) investigated the formability of austenitic stainless steel 316 at elevated temperatures for circular blank deep drawing cup. ANN model is developed to predict the cup thickness at different locations. Liu et al. (2015) proposed ANN model for prediction of accurate radius and application in incremental in-plane bending.

Based on the literature review, the salient features of major research work in the area of applications of ANN in sheet metal work are summarized in Table 1. Form the literature review, it can be concluded that worldwide researchers have used ANN technique for specific applications like process control, process planning, quality control, prediction of bending, feature recognition, tool design, cutting tool selection etc. However, no work is reported in the literature which is focused on prediction of life of compound die using ANN.

Table 1 Summary of major research work the area of applications of ANN in sheet metal work

Authors	System details	Remark
Forcellese et al. (1998)	Used BP algorithm and bipolar sigmoid activation function for prediction of the bend angle	Requires trained person to operate
Wu et al. (1999)	Used logistic, linear threshold or hard limiting (on/off) as activation function for investigation of wrinkling and buckling of sheet metal parts	System takes more time
Kim and Kim (2000)	Used three-layer NN and BP algorithm for training of finite element simulation of sheet metal parts	Requires experienced person
Hambli and Guerin (2003)	Used three-layer feed-forward NN and MLP for prediction of optimum punch-die clearance in sheet metal blanking process	Developed for specific application like sheet metal blanking
Slomp and Klingenberg (2004)	Used pattern recognition for monitoring and diagnosis of punching/blanking process	Recognition takes more time
Pathak et al. (2005)	Used sigmoid function and BP algorithm for prediction responses of the sheet metal bending process	Trained person is required to operate
Liu et al. (2007)	Used GA-ANN techniques. Also BP algorithm is used to solve the problem of spring-back in sheet metal forming	Requires trained person
Nasrollahi and Arezoo (2012)	Used MLP, BP NNs with LM training function for prediction of spring-back on sheet metal	Developed for specific application
Liu et al. (2015)	Used back propagation neural network for prediction of accurate radius in-plane bending	Developed for specific application

2 Proposed ANN Model for Prediction of Life of Compound Die

Life of compound die is dependent on its active parts including die block, punches (piercing and blanking) and stripper. The life of these active parts depends on various factors such as sheet thickness, sheet material, geometry of sheet metal part, and die material. To predict die life, punch force and stripping force need to be calculated. Punch force required for stamping depends on sheet thickness, shear strength of sheet material and area of design feature of sheet metal part. Stripping force is generally taken as 10 % of punch force. The methodology of development of proposed ANN model for prediction of life of compound die includes following steps (Kashid and Kumar 2014a, b; Kashid et al. 2015):

Step 1 3-D drawings of active components of compound die automatically generated by the developed system ESIDCD (*E*xpert *S*ystem for *I*ntelligent *D*esign of *C*ompound *D*ies) as described in Chap. 8 are given as inputs for prediction of die life

Step 2 FE analysis of CAD models of these active components is performed using Ansys (workbench) software. In Ansys workbench software user has to enter material properties of die components. Generally active die components are made of SVERKER3 (AISI D3), SEVERKER21 (AISI D2), AISI 52100 (EN-31, AISI 52100), and AISI 310 materials (Kumar and Singh 2007)

Step 3 Punch force as determined by the previous expert system module PUNFR is applied on the punches for EF analysis. Stripping force is taken as 10 % of punch force. Force applied on die block is taken as 5 % of punch force (Campbell 2013).On applying these forces on die components, maximum ($\sigma_{\max}$) and minimum ($\sigma_{\min}$) principal stress values are determined from FE analysis

Step 4 Following equations are used for calculation of number of cycles (Graham 1968):

$$N = \left(\frac{S_n}{S_e}\right)^{\frac{1}{b}} 10^x \tag{2a}$$

where,

N Number of cycles

S_n Fatigue strength (as calculated from Goodman equation)

S_e Endurance limit for AISI 310

$$S_e = 0.5 \times S_u \tag{3}$$

where,

S_u Ultimate tensile strength of AISI 310

$$b = -\frac{1}{3}\log\left(\frac{\sigma_a}{S_e}\right) \tag{4}$$

where

σ_a Amplitude stress

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2} \tag{5}$$

The value of 'x' in the term 10^x in Eq. (1) is obtained from S–N curve approximation (Graham 1968) as shown in Fig. 3.

Goodman equation as given as under

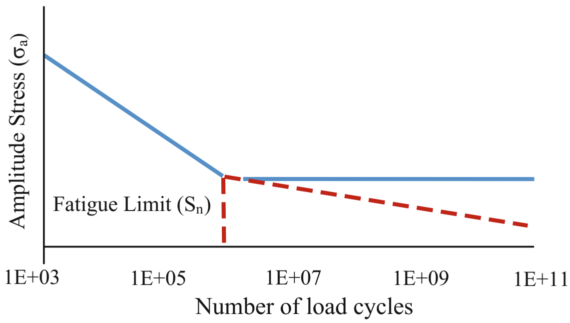

Fig. 3 S–N curve approximation for tool steel (D2) (Kazymyrovych 2010)

$$\left(\frac{\sigma_a}{S_n}\right) + \left(\frac{\sigma_m}{S_u}\right) = 1 \tag{6}$$

where,

σ_m Mean stress

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \tag{7}$$

From S–N curve approximation curve value of 'x' is 10. Therefore, the Eq. (2a) becomes

$$N = \left(\frac{S_n}{S_e}\right)^{\frac{1}{b}} \times 10^6 \tag{2b}$$

Step5 Thereafter, an ANN model is developed using MATLAB software. There are several activation functions available to use in an ANN model. Sigmoid (logistic) function is chosen as activation (transfer) function in this study as below:

$$\text{Output}_{(j)} = f\,\text{net}\,\text{Output}_{(j)} = \frac{1}{1 + \mathrm{e}^{-\text{net}_j}} \tag{8}$$

Before feeding the data into neural network tool box of MATLAB first activity is to normalize FE analysis data. Normalizing is the function to improve the accuracy of ANN model. There are five type of normalizing FEM analysis data such as statical or Zscore normalization, maximum and minimum normalization, sigmoid or softmax normalization, energy normalization, and principal part analysis or Hotelling transform. In the present ANN model maximum and minimum normalization method is used. Maximum and minimum normalization formula is as follows

$$V' = \left[\frac{V - \min(v)}{\max(v) - \min(v)}\right] \quad (9)$$

In the present ANN model backpropagation (BP) algorithm is used for training FE analysis data. This algorithm minimizes the total mean-square error between the actual outputs and the desired outputs. For proposed ANN model, two-third data for training and one-third data for testing are selected. This data is fed into neural network toolbox of MATLAB. The ANN is well trained using the results of FE analysis. A three-layer neural network is used for development of model. There are many training algorithms available, but most popular one is the Lavenberg–Marquardt backpropagation algorithm (Verlinden et al. 2008). This algorithm is used for prediction of life of compound die. However, the number of neurons in the hidden layer depends on the complexity level of the function. If the number of inflection points is high then more number of neurons in the hidden layer is needed. More than 250 sets of data of various process parameters are utilized for training of ANN.

3 Validation of the Proposed ANN Model

The developed ANN model has been tested on active components (die block, stripper and punches) of compound die modeled by the expert system ESIDCD (as described in Chap. 8) for various sheet metal parts. A sample run of this model on a compound die designed for one example sheet metal part (Fig. 4) is demonstrated here. This compound die is capable to produce 5,00,000 number of sheet metal parts during its entire life as per the information received from the industry M/s D. D. Engineering Pvt. Ltd., Pune, India.

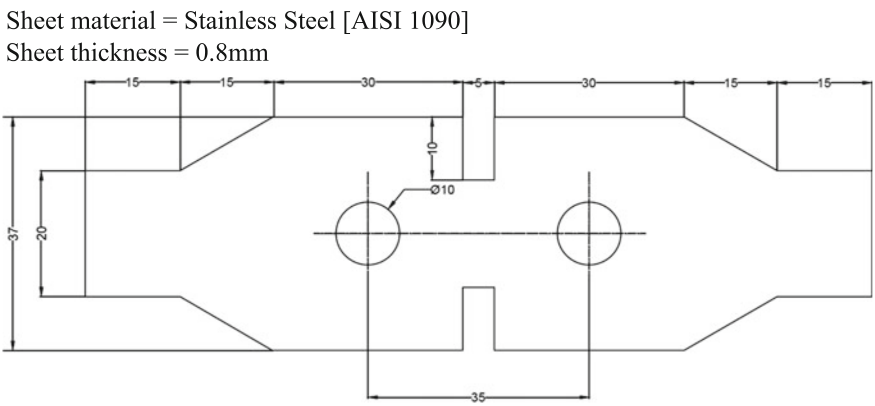

Fig. 4 Example part (all dimensions are in mm) (M/s D. D. Engineering Pvt. Ltd., Pune, India)

The material SVERKER3 (AISI D3) for piercing punch and blanking punch, SVERKER21 (AISI D2) for die block, and AISI 310 for stripper are used for FE analysis (as per the information received from the said industry). Mechanical properties of these materials are given in Tables 2, 3 and 4.

More than 250 sets of data of various process parameters are utilized for training of ANN. The outputs of developed FEA model are depicted in Figs. 5, 6, 7, 8, 9, 10, 11 and 12 and summarized in Tables 5, 6, 7 and 8. The proposed ANN model predicts life of compound die in terms of number of cycles (means number of sheet metal parts that can be produced) as 474,456 which is almost equal to the actual number of sheet metal parts produced in the said industry using this compound die. Best validation performance results are shown in Figs. 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23 and 24. Figures 25, 26, 27 and 28 depict the comparison of analytical result and ANN predicted result for maximum principal stress versus number of cycles of die block, stripper, piercing punch and blanking punch. The maximum error is 0.95 as calculated using the values shown in Tables 5, 6, 7 and 8. The difference between analytical and ANN predicted results is very small which confirms the ability of developed ANN model to predict life of components of compound die accurately. The comparison shows that the prediction of die life by ANN model closely follows the analytical results.

Table 2 Mechanical properties of SVERKER 3 (www.uddeholm.com)

Compressive strength	2210 MPa
Density	7700 kg/m^3
Ultimate tensile strength	1400 MPa
Shear modules	77,600 MPa
Modulus of elasticity	194,000 MPa
Poissons ratio	0.27

Table 3 Mechanical properties of SVERKER 21 (www.uddeholm.com)

Compressive strength	2200 MPa
Density	7700 kg/m^3
Ultimate tensile strength	1400 MPa
Shear modules	84,000 MPa
Modulus of elasticity	210,000 MPa
Poissons ratio	0.25

Table 4 Mechanical properties of AISI 310 (www.aperam.com)

Compressive strength	960 MPa
Density	5000 kg/m^3
Ultimate tensile strength	580 MPa
Shear modules	73,000 MPa
Modulus of elasticity	200,000 MPa
Poissons ratio	0.27

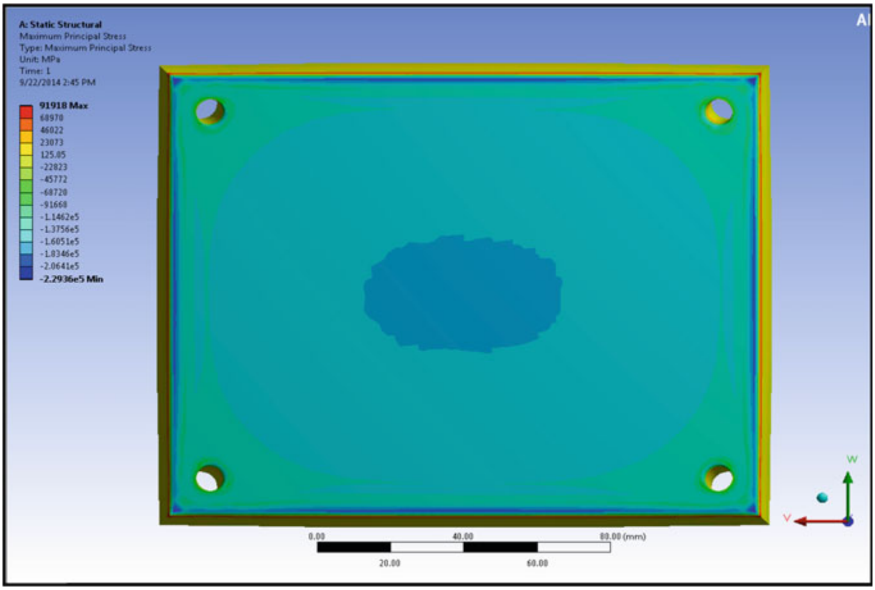

Fig. 5 Maximum principal stresses of die block

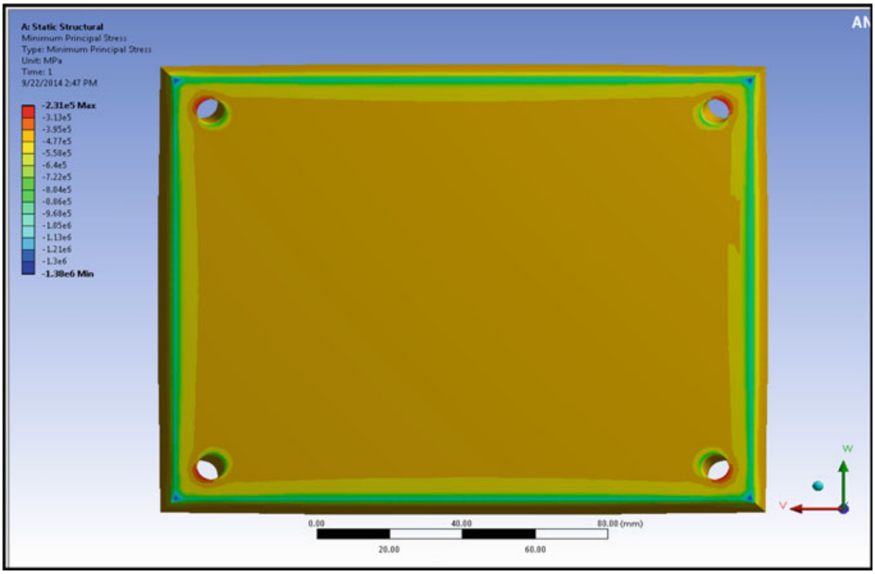

Fig. 6 Minimum principal stresses of die block

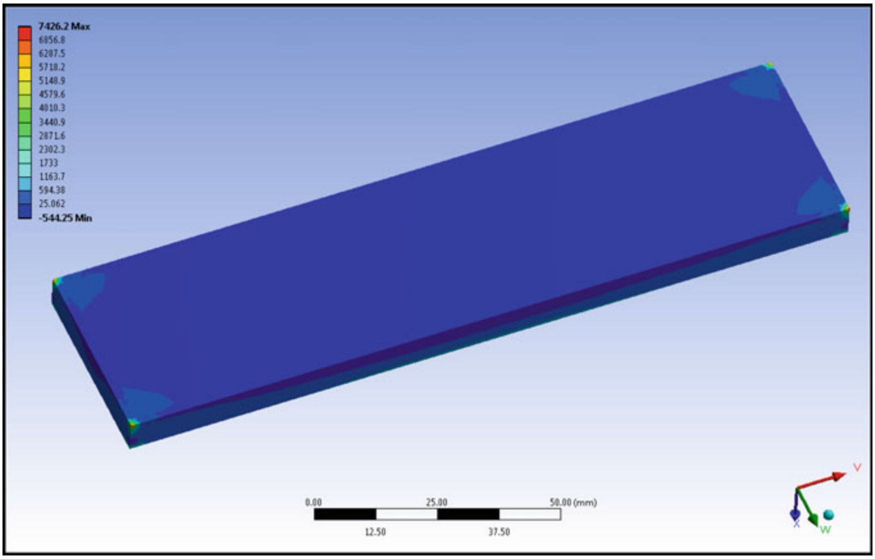

Fig. 7 Maximum principal stresses of stripper

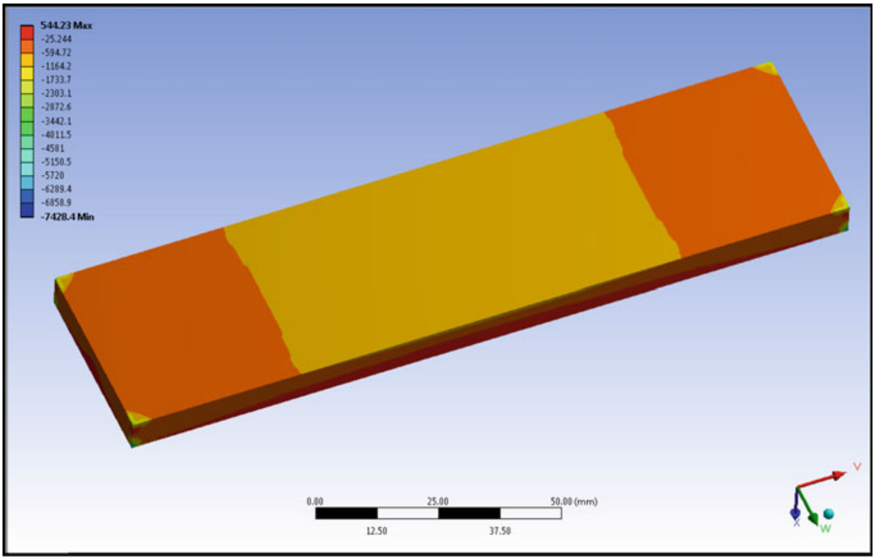

Fig. 8 Minimum principal stresses of stripper

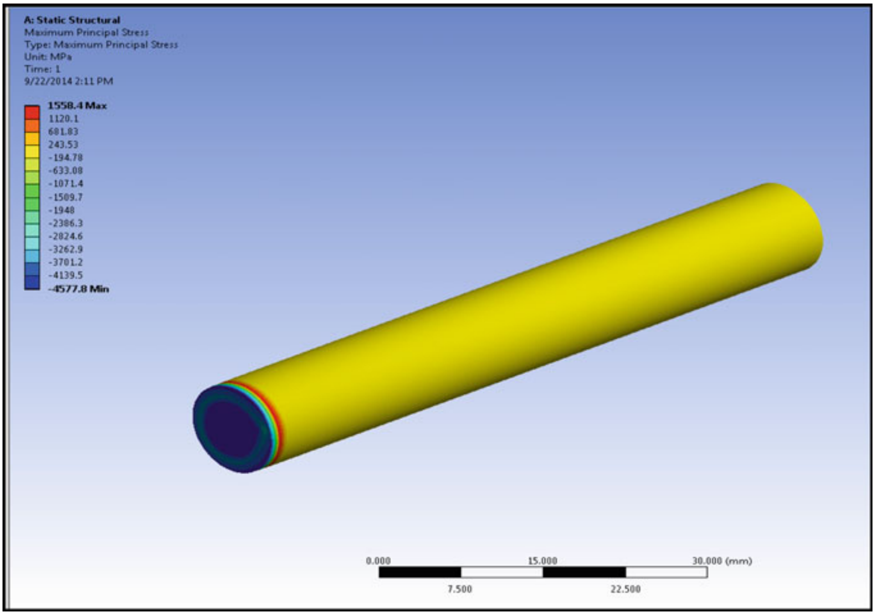

Fig. 9 Maximum principal stresses of piercing punch

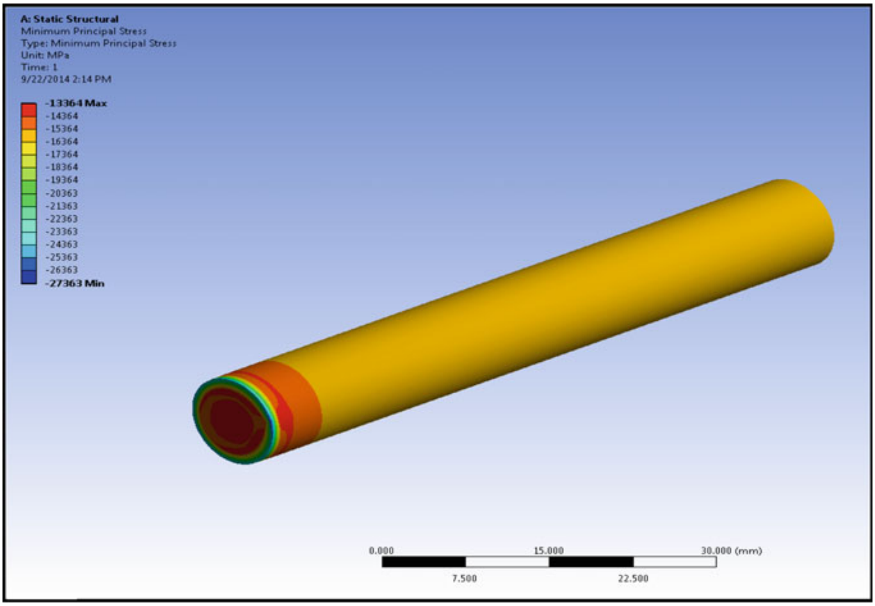

Fig. 10 Minimum principal stresses of piercing punch

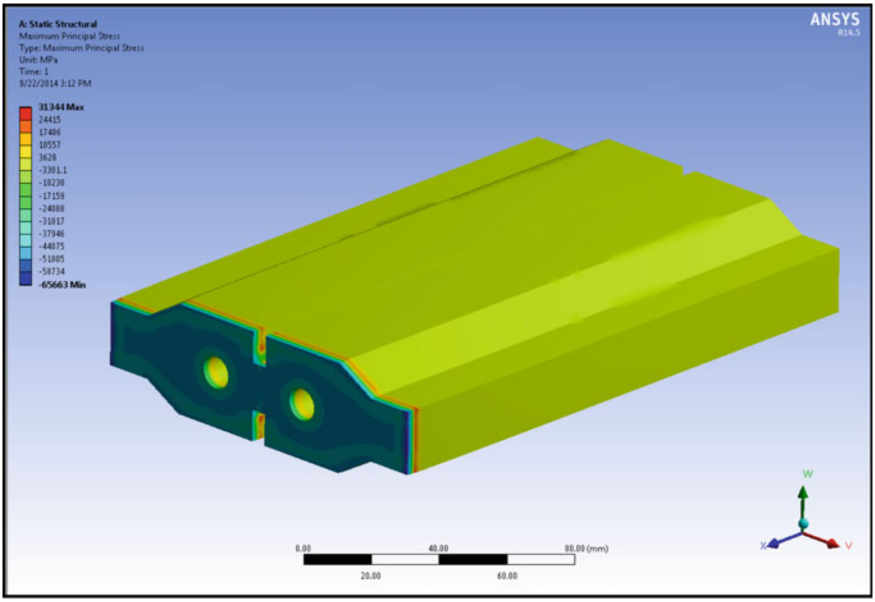

Fig. 11 Maximum principal stresses of blanking punch

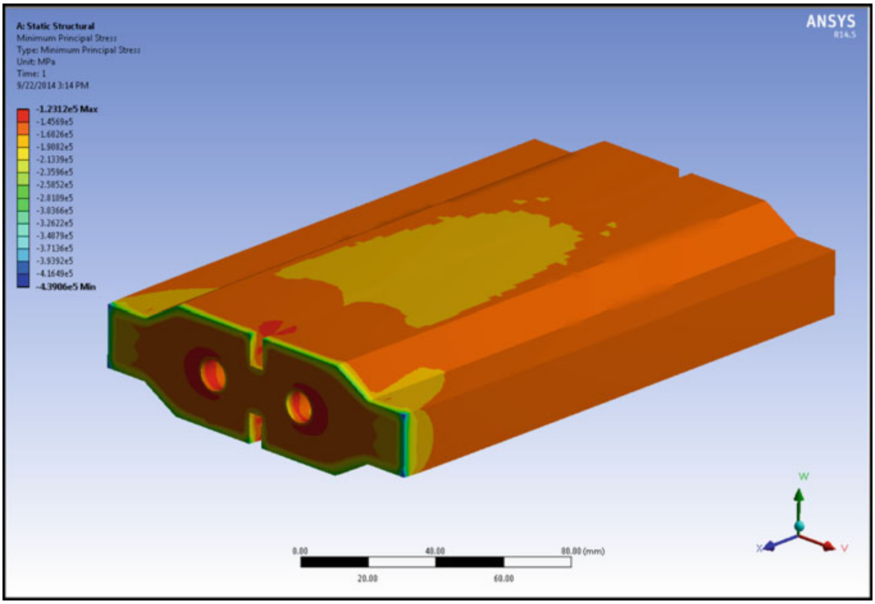

Fig. 12 Minimum principal stresses of blanking punch

Table 5 A sample of output of FE analysis, analytical result, and ANN result of die block

Die block stresses in (MPa)					
Max. principal stress in (MPa)	Min. principal stress in (MPa)	Amplitude stress (σ_a)	Mean stress (σ_m)	Analytical results (number of cycles)	ANN predicted results (number of cycles)
−2.29E+05	−1,378,100.0	575,012.6	−803,087.445	692,251	660,892
−228,074.89	−1,373,510.0	573,360.1	−800,149.89	691,586	658,527
−226,789.78	−1,368,920.0	571,707.7	−797,212.335	690,917	655,988
−225,504.67	−1,364,330.0	570,055.2	−794,274.78	690,244	653,313
−224,219.56	−1,359,740.0	568,402.8	−791,337.225	689,567	650,497
−222,934.45	−1,355,150.0	566,750.3	−788,399.67	688,886	647,546
−221,649.34	−1,350,560.0	565,097.9	−785,462.115	688,201	644,459
−220,364.23	−1,345,970.0	563,445.4	−782,524.56	687,512	641,231
−219,079.12	−1,341,380.0	561,793	−779,587.005	686,819	637,867
−217,794.01	−1,336,790.0	560,140.6	−776,649.45	686,122	634,368
−216,508.9	−1,332,200.0	558,488.1	−773,711.895	685,421	630,743
−215,223.79	−1,327,610.0	556,835.7	−770,774.34	684,715	626,989
−213,938.68	−1,323,020.0	555,183.2	−767,836.785	684,005	623,110
−212,653.57	−1,318,430.0	553,530.8	−764,899.23	683,291	619,117
−211,368.46	−1,313,840.0	551,878.3	−761,961.675	682,572	615,010

Table 6 A sample of output of FE analysis, analytical result, and ANN result of stripper

Stripper stresses in (MPa)					
Max. principal stress in (MPa)	Min. principal stress in (MPa)	Amplitude stress (σ_a)	Mean stress (σ_m)	Analytical results (number of cycles)	ANN predicted results (number of cycles)
−544.3	−7428.4	3458.015	−3970.385	311,387	300,025
−512.4	−7396.5	3458.01	−3938.5	305,345	298,125
−480.5	−7364.6	3458.005	−3906.615	299,379	290,669
−448.6	−7332.7	3458	−3874.73	293,488	285,661
−416.7	−7300.8	3457.995	−3842.845	287,671	280,124
−384.9	−7269.0	3457.99	−3810.96	281,930	276,002
−353.0	−7237.1	3457.985	−3779.075	276,262	271,102
−321.1	−7205.2	3457.98	−3747.19	270,668	265,332
−289.2	−7173.3	3457.975	−3715.305	265,147	261,001
−257.3	−7141.4	3457.97	−3683.42	259,698	256,663
−225.5	−7109.5	3457.965	−3651.535	254,322	251,339
−193.6	−7077.6	3457.96	−3619.65	249,018	245,029
−161.7	−7045.7	3457.955	−3587.765	243,785	240,003
−129.8	−7013.8	3457.95	−3555.88	238,624	235,789
−97.9	−6981.9	3457.945	−3523.995	233,532	231,008

Table 7 A sample of output of FE analysis, analytical result and ANN result of piercing punch

Piercing punch stresses in (MPa)					
Max. principal stress in (MPa)	Min. principal stress in (MPa)	Amplitude stress (σ_a)	Mean stress (σ_m)	Analytical results (number of cycles)	ANN predicted results (number of cycles)
−4577.8	−27,363.0	11,404.87	−15,958.13	546,154	534,956
−4553.3	−27,307.0	11,389.15	−15,917.865	544,944	534,261
−4528.7	−27,251.0	11,373.42	−15,877.6	543,731	533,509
−4504.2	−27,195.0	11,357.7	−15,837.335	542,516	532,720
−4479.6	−27,139.0	11,341.97	−15,797.07	541,298	531,901
−4455.1	−27,083.1	11,326.25	−15,756.805	540,077	531,048
−4430.6	−27,027.1	11,310.52	−15,716.54	538,855	530,161
−4406.0	−26,971.1	11,294.8	−15,676.275	537,629	529,241
−4381.5	−26,915.1	11,279.07	−15,636.01	536,401	528,282
−4356.9	−26,859.1	11,263.35	−15,595.745	535,170	527,290
−4332.4	−26,803.1	11,247.62	−15,555.48	533,937	526,264
−4307.9	−26,747.1	11,231.9	−15,515.215	532,701	525,201
−4283.3	−26,691.1	11,216.17	−15,474.95	531,463	524,108
−4258.8	−26,635.1	11,200.45	−15,434.685	530,222	522,976
−4234.2	−26,579.1	11,184.72	−15,394.42	528,979	521,808

Table 8 A sample of output of FE analysis, analytical result, and ANN result of blanking punch

Blanking punch stresses in (MPa)					
Max. principal stress in (MPa)	Min. principal stress in (MPa)	Amplitude stress (σ_a)	Mean stress (σ_m)	Analytical results (number of cycles)	ANN predicted results (number of cycles)
−65,663.0	−439,060.0	186,892.5	−252,167.49	618,927	602,021
−65,275.0	−437,796.5	186,454.8	−251,341.72	618,101	600,605
−64,887.0	−436,533.0	186,017	−250,515.95	617,271	599,105
−64,498.9	−435,269.4	185,579.3	−249,690.18	616,438	597,521
−64,110.9	−434,005.9	185,141.5	−248,864.41	615,600	595,858
−63,722.9	−432,742.4	184,703.8	−248,038.64	614,759	594,107
−63,334.9	−431,478.9	184,266	−247,212.87	613,913	592,276
−62,946.9	−430,215.4	183,828.3	−246,387.1	613,064	590,357
−62,558.8	−428,951.8	183,390.5	−245,561.33	612,210	588,358
−62,170.8	−427,688.3	182,952.8	−244,735.56	611,353	586,280
−61,782.8	−426,424.8	182,515	−243,909.79	610,491	584,118
−61,394.8	−425,161.3	182,077.3	−243,084.02	609,626	581,882
−61,006.8	−423,897.8	181,639.5	−242,258.25	608,756	579,570
−60,618.7	−422,634.2	181,201.8	−241,432.48	607,883	577,179
−60,230.7	−421,370.7	180,764	−240,606.71	607,005	574,721

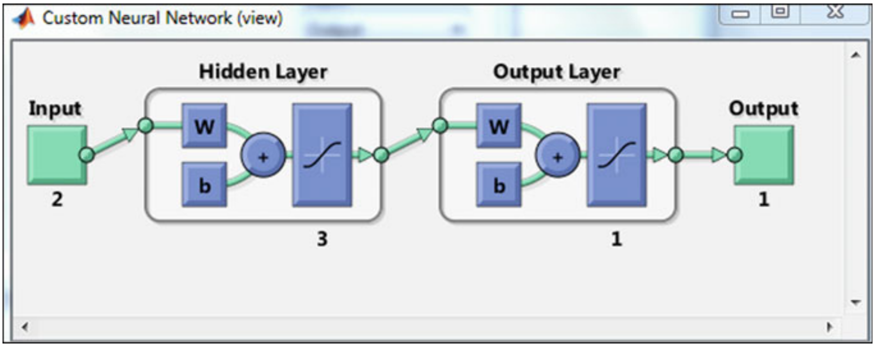

Fig. 13 Number of layers 2 and 3 neurons

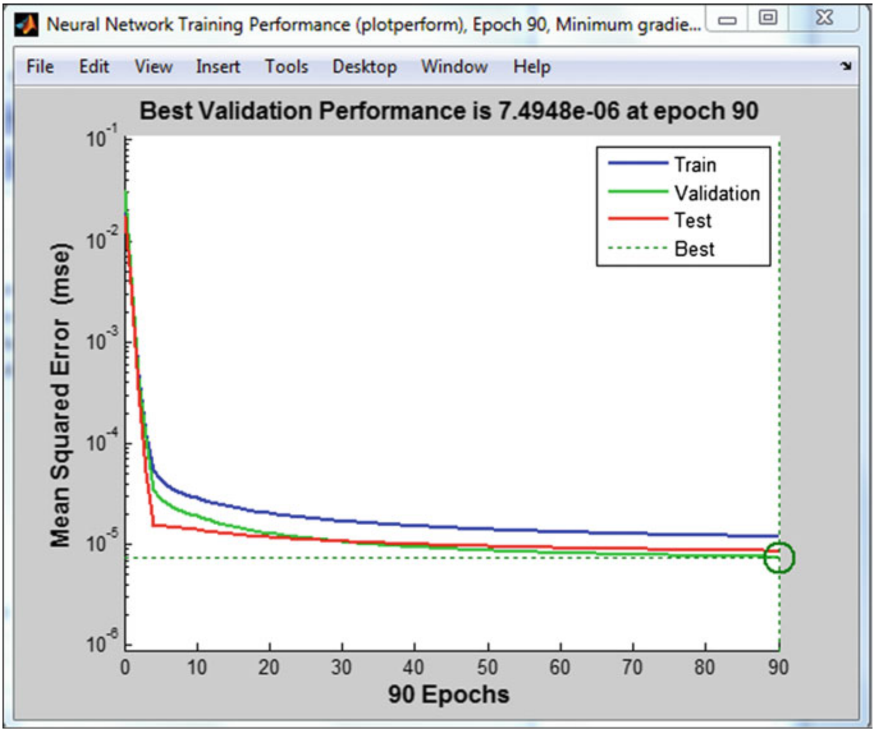

Fig. 14 Minimum error for 2 layers and 3 neurons

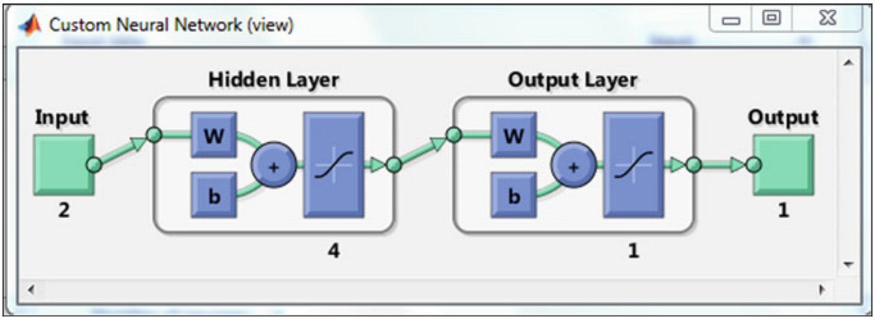

Fig. 15 Number of layers 2 and 4 neurons

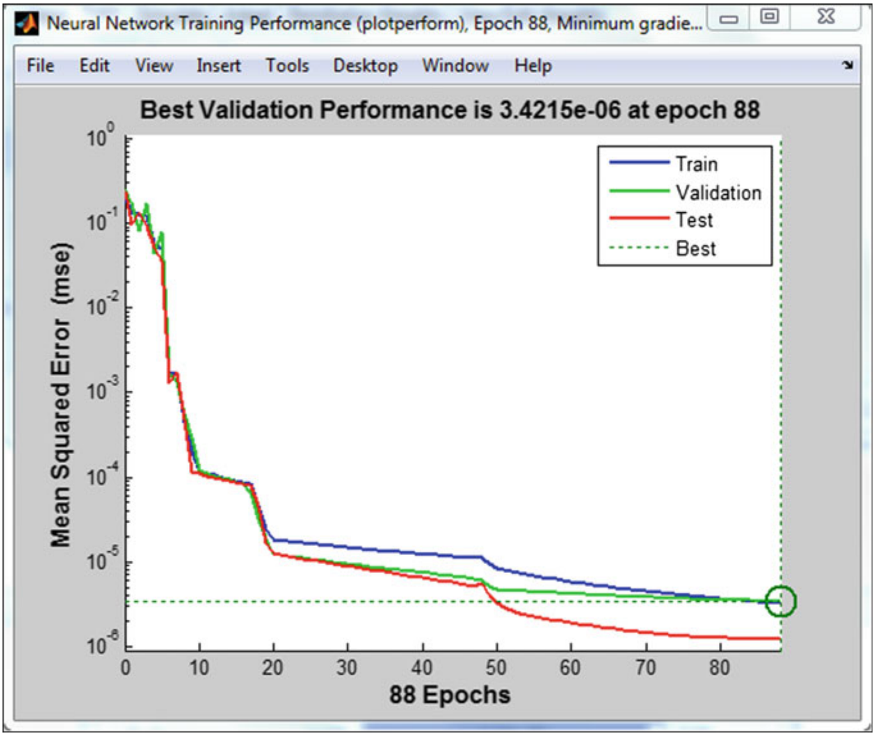

Fig. 16 Minimum error for 2 layers and 4 neurons

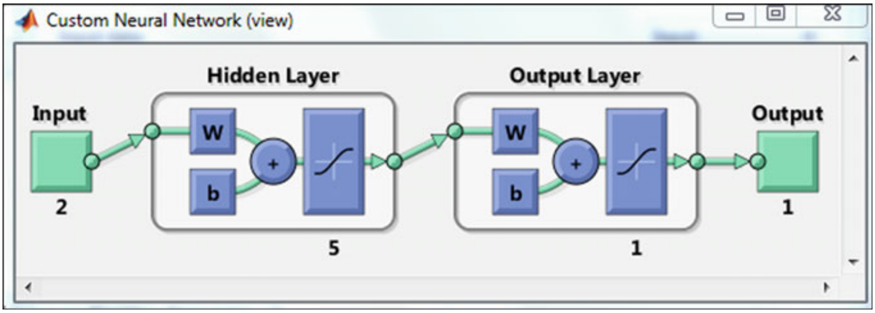

Fig. 17 Number of layers 2 and 5 neurons

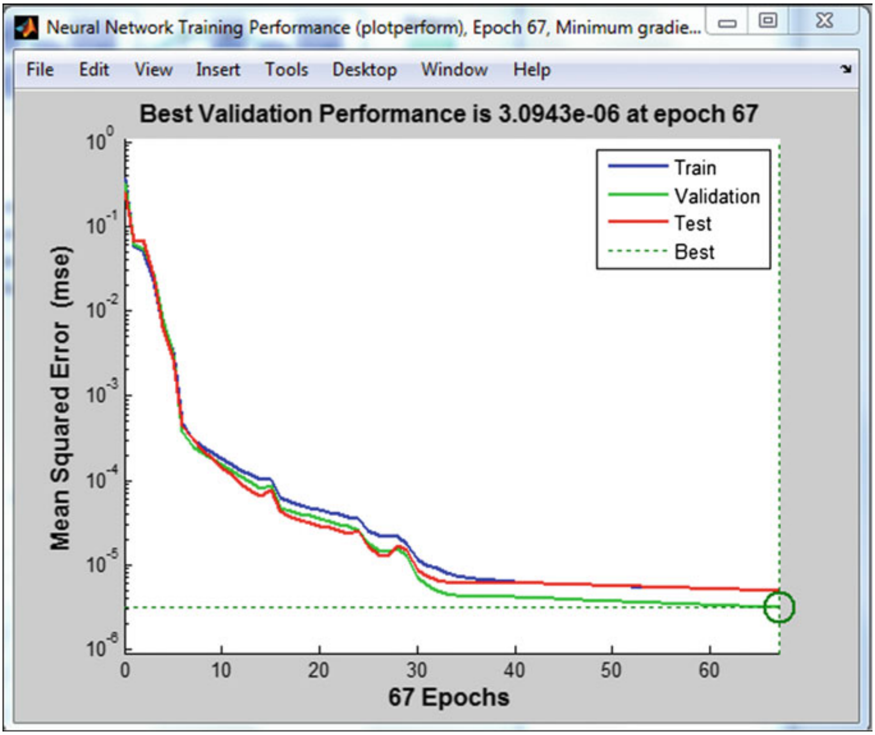

Fig. 18 Minimum error for 2 layers and 5 neurons

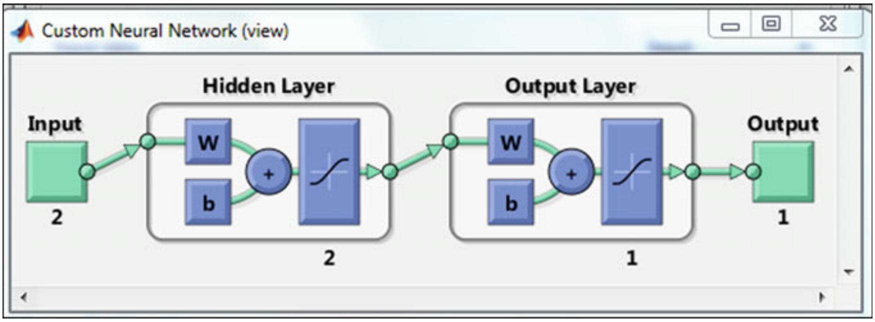

Fig. 19 Number of layers 3 and 2 neurons

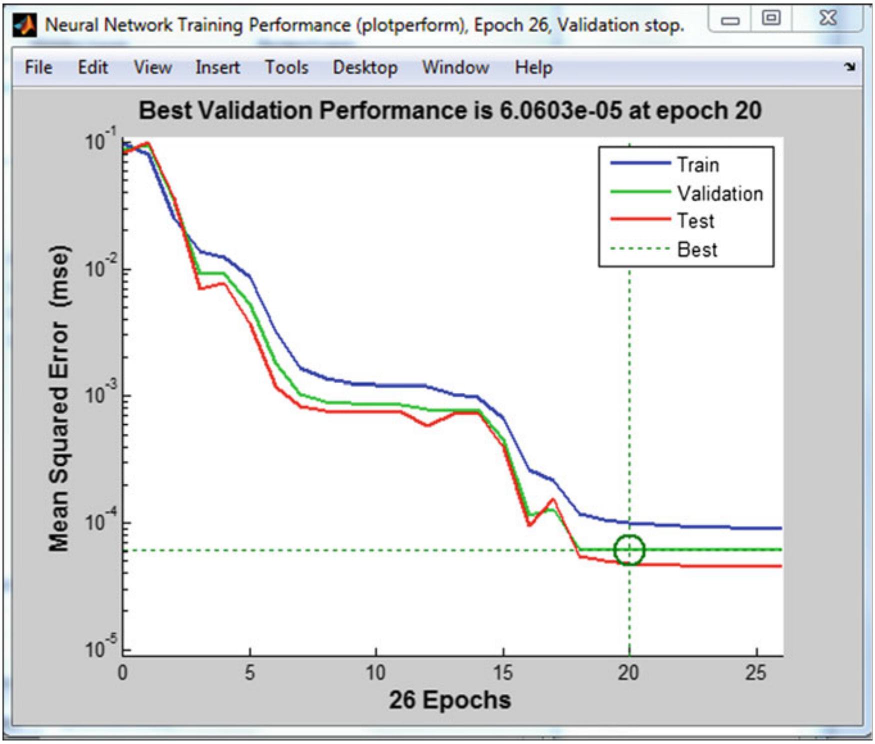

Fig. 20 Minimum error for 3 layers and 2 neurons

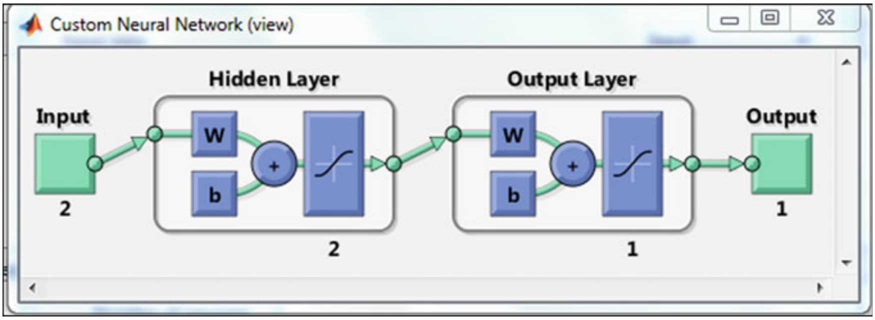

Fig. 21 Number of layers 4 and 2 neurons

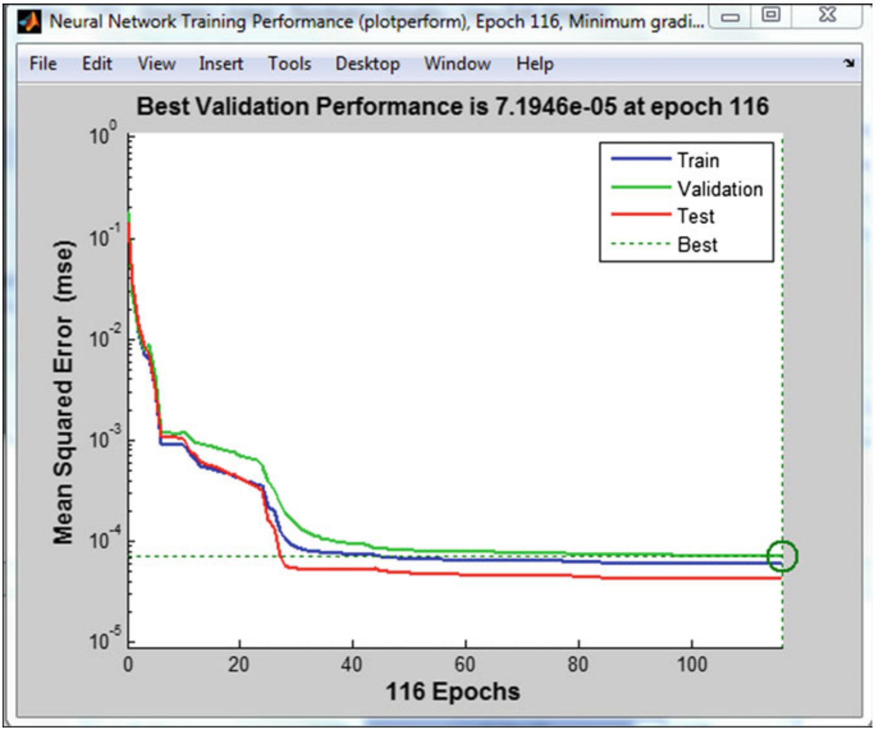

Fig. 22 Minimum error for 4 layers and 2 neurons

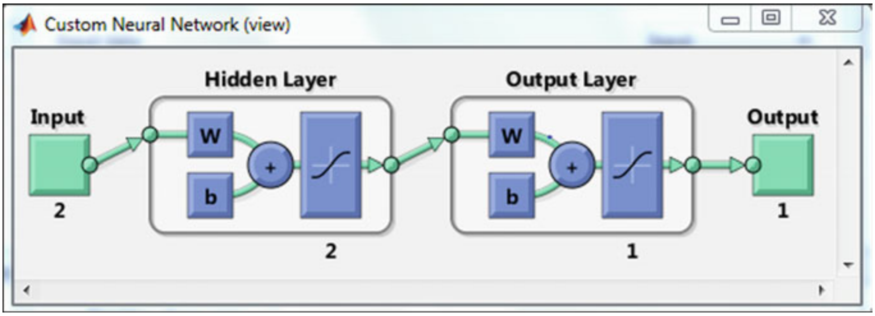

Fig. 23 Number of layers 5 and 2 neurons

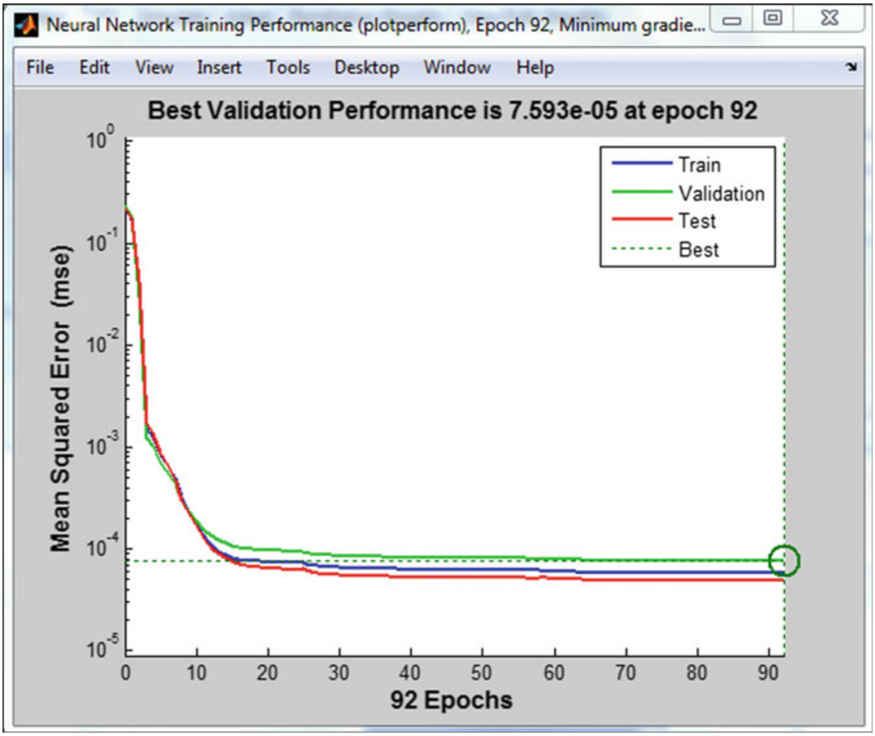

Fig. 24 Minimum error for 5 layers and 2 neurons

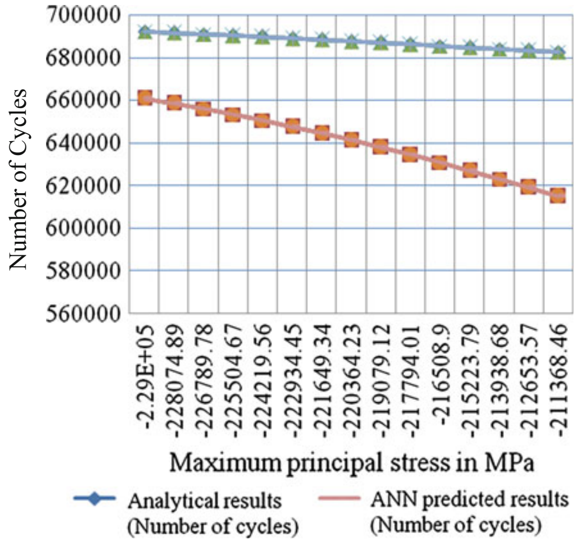

Fig. 25 Comparison of analytical result and ANN predicted result for maximum principal stress of die block versus number of cycle

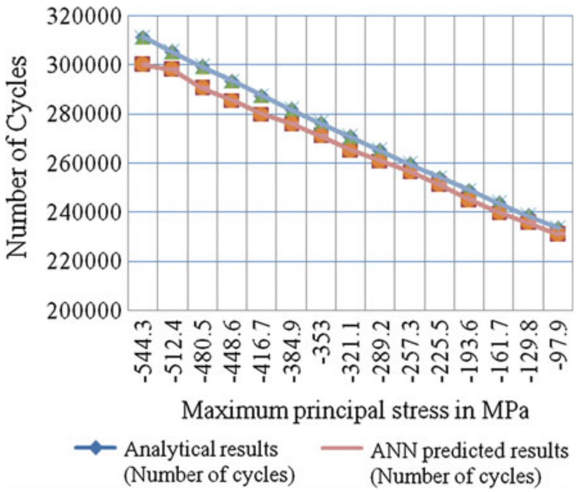

Fig. 26 Comparison of analytical result and ANN predicted result for maximum principal stress of stripper versus number of cycle

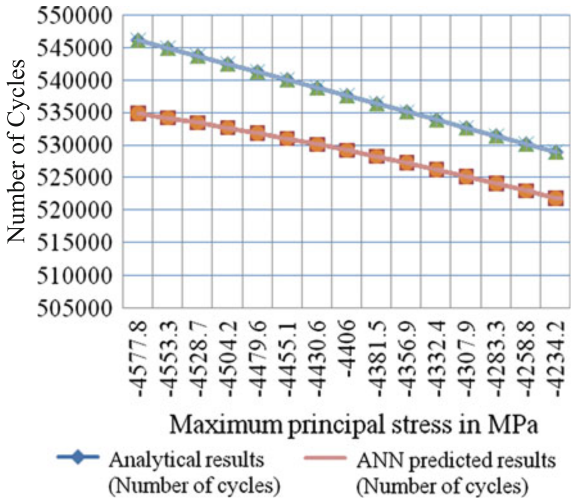

Fig. 27 Comparison of analytical result and ANN predicted result for maximum principal stress of piercing punch versus number of cycle

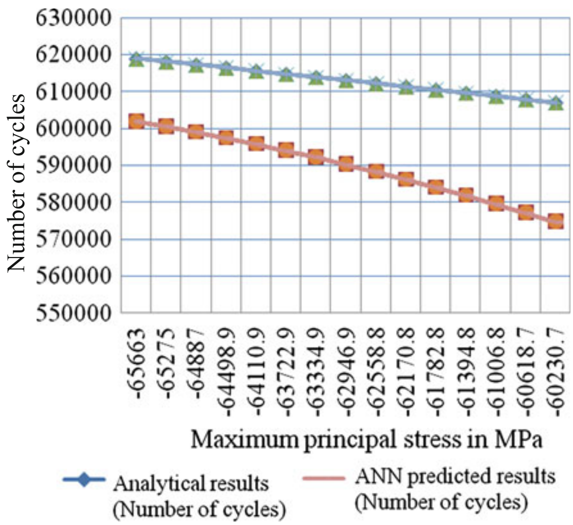

Fig. 28 Comparison of analytical result and ANN predicted result for maximum principal stress of blanking punch versus number of cycle

4 Conclusion

In this chapter, application of ANN for prediction of life of compound die is described. The developed ANN model is capable of accomplishing the tedious and time-consuming task of prediction of life of compound die in a very short time period. The model has been tested successfully on various compound dies taken from sheet metal industries. A sample run on a typical compound die demonstrated the usefulness of this model. The outcome of developed ANN model is very useful for sheet metal industries to accomplish the above experience-based task.

The similar approach can be used to develop ANN models for prediction of life of other single operation and multi-operation dies.

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Knowledge-Based System for Automatic Design of Bending Dies

Deepak Panghal, Shailendra Kumar and Hussein M.A. Hussein

1 Introduction

Sheet metal parts are widely used in automobiles, electrical and electronic equipments, computer hardware, home and office furniture, kitchen utensils, and other similar products. Sheet metal operations are used to produce these parts. Sheet metal operations are performed using punch and die setup, commonly known as die or press tool, in a press machine. A die has a complex structure consisting of several components. Die block, punch(es), stripper plate, punch plate, back plate, die-set, etc., are some major components of a die. To manufacture good quality parts, die design is an important activity in tool design department of sheet metal industries.

Bending shapes are obtained using bending process. Bending is one of the most common sheet metal forming processes. It is used to form the various shapes like L, U, V, and Z from sheet metal blanks. It improves the stiffness of blank by increasing its moment of inertia. Bending process has wide applications in electrical, electronic, automobile, aircraft, aerospace, pharmaceutical, refrigeration, and air-conditioning industries. Figure 1 shows a typical bending process. The downward movement of punch applies force on the blank which results in bending. Thereafter, the punch moves back in upward direction and the bent part is extracted from the die. The blank undergoes compressive stress on the concave side and

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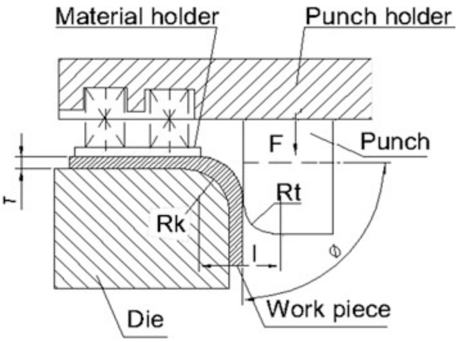


Fig. 1 A typical bending process

tensile stress on convex side during bending operation. The inner radius of bent part depends on the radius of die opening.

Bending process is performed using a suitable type of bending die mounted in a press machine. Bending dies are generally classified into three types (Boljanovic 2004):

(i) Wiping die,
(ii) U-bending die, and
(iii) V-bending die.

Wiping die is used to perform edge bending as shown in Fig. 1. U-bending die is used to produce U shaped bending parts. Similarly, V-bending die is used to form V-shaped bending parts. The sheet metal blank is bent between a V-shaped punch and die in V-bending die.

1.1 Design of Bending Dies

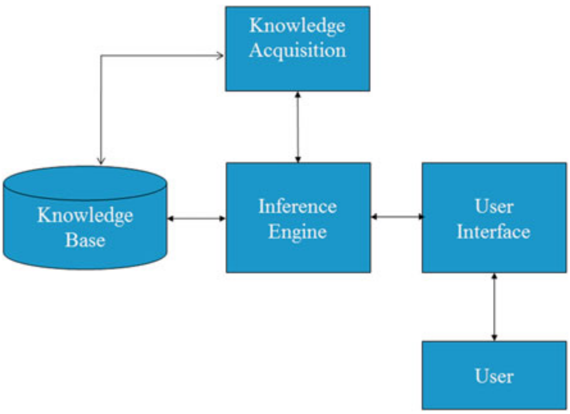
Die design is a highly specialized area and therefore usually performed by experienced and highly skilled die designers in sheet metal industries (Singh and Rao 1997; Kumar and Singh 2004, 2007; Lin and Hsu 2008; Narayanan 2010). In die design process, die designer needs to recognize design features of sheet metal part, check the features from manufacturability point of view, determine process planning parameters, select proper size of die components, and lastly prepare the drawings of die components and die assembly. Manual process of design of bending die is complex, time consuming, error prone, and skill-intensive (Cheok and Nee 1998a, b; Kumar and Singh 2011). Nowadays, some commercial softwares (AutoCAD, Inventor, CATIA, Pro-E, IDEA, Solid Edge, Unigraphics NX, CADCEUS, etc.) are being used in sheet metal industries for die design. These softwares assist the die designer in simple calculations, drafting, and storage and retrieval of data and drawings. But these systems are not capable to automate the die design process and need experienced persons to operate and interpret the results.

Few software packages are developed specifically for the design of bending dies. For example, a dedicated tool "act/unfold" for unfolding of bending parts is developed by M/s Alma CAM of USA. The tool is unfolding software that uses table approach as well as neutral axis method. Since the tool is independently developed so integration approach is missing. M/s Autodesk's Inventor software has a sheet metal modeling environment in which sheet metal bending parts can be modeled. M/s Dassualt System's software CATIA has a tool named as generative sheet metal Design. The main features of the software are associative and dedicated sheet metal feature-based modeling, concurrent engineering between the unfolded or folded part representations, access to predeveloped standards tables, dedicated drawing capability including unfolded view and specific setting. The specialized CAD software "MetaBEND" is a product of M/s Metamation of United States. Key features of the CAD system are bend sequencing and collision checking optimized tool selection.

1.2 Knowledge-Based System

Knowledge-based system (KBS) is an important technique of artificial intelligence (AI) (Poole and Mackworth 2010). It is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution (Feigenbaum 1981). As depicted in Fig. 2, a KBS has three main elements—knowledge base, inference mechanism, and user interface. The knowledge base contains domain knowledge, which may be expressed as any combination of IF-THEN rules, factual statements, frames, objects, procedures and cases. The inference mechanism allows manipulating the stored knowledge for solving problems. User interface is a platform of interaction between user and system. The use of KBS is proliferating in many domains, where their applications are proving to be critical in the process of

Fig. 2 Main elements of a KBS



decision support and problem solving. KBS has wide applications in engineering domain such as state transition analysis, production planning, advisory system, electronic power planning, automobile process planning, system development, knowledge verification/validation, knowledge base maintenance, scheduling strategy, communication system fault diagnosis, material processing design, resource utilization, probabilistic fault diagnosis, load scheduling, geoscience, sensor control, etc. (Kusiak 1990; Meziane et al. 2000; Liao 2005).

2 Literature Review

In the past sheet metal forming was heavily dependent on skills of workers. However, with increased production demands, this procedure was replaced by automated stamping, which today is one of the most widely used manufacturing process to plastically deform sheet metals into desired shapes. With the advancement in the area of CAD/CAM and artificial intelligence (AI), some researchers (Karima and Richardson 1987; Shpitalni and Saddan 1994; Cheok and Foong 1996; Huang et al. 1996; Singh and Sekhon 1998; Duflou et al. 1999; Cakir et al. 2005; Kim et al. 2006; Kumar and Singh 2011) started to exploit these techniques for the design of stamping dies.

Major published work related to the applications of CAD and KBS in the area of process planning of bending parts, and bending die design is discussed in this section.

2.1 *Process Planning of Bending Parts*

Worldwide researchers have applied research efforts to ease the complexity of process planning of sheet metal parts. For example, Hoffmann et al. (1992) developed a bending sequence generator and tool selection as part of a computerized process planning tool labeled as MANICAP. Shpitalni and Saddan (1994) proposed a technique for automatic determination of bending sequences in sheet metal parts. In this technique, the problem of automatic tool selection and bending sequence determination are formulated as a graph search problem. Vin et al. (1994) reported a bend sequencing approach which provides emphasis on the accuracy aspect. They used integrated approach of bend sequencing with other process planning parameters like planning and selection of tools, and blank size. Huang and Leu (1998) studied the effects of process variables in V-bending of steel sheet. Gupta et al. (1998) developed a process planning system for sheet metal parts for generation of possible bending sequences and manufacturing costs, selection of punches and dies, interference checking, gripper selection and robot motion plan, and near optimal plan development. Duflou et al. (1999) derived an algorithm for design verification and automatic process planning for bent sheet metal parts. Later they (Duflou et al. 2005) presented a tool selection methodology to be integrated in the automatic bend sequencing system. Shigeru and Koguchi (2002) proposed a method, which generates bending sequence for a sheet metal part handled by a robot. Rico et al. (2003) developed a system to obtain valid bending sequences automatically according to the possible tool–part collisions and tolerances. Sousa et al. (2006) presented an optimization method applied to the design of V and U-bending sheet metal processes. Mkaddem and Saidane (2007) examined springback in wiping die bending process using experimental approach and response surface methodology (RSM). Bozdemir and Golcu (2008) defined the springback angle with minimum error using the best reliable ANN training algorithm. Fu et al. (2010) optimized the process of multiple-step incremental air-bending forming of sheet metal by using genetic algorithm-back propagation neural network prediction and finite-element model simulation. Kontolatis and Vosniakos (2010) applied sheet metal bending processes in a multitude of mechanical parts. Thipprakmas and Phanitwong (2011) described process parameters of spring back in V-bending process using Taguchi technique. Lin (2012) proposed an approach of bending sequence for process planning of bending parts.

2.2 Bending Die Design

Since its emergence in the 1950s, AI has provided several techniques that have been used in efforts to solve some complex and narrow domain industrial problems. The KBS/expert system (ES), neural networks (NN), fuzzy logic (FL), multi agents (MA), genetic algorithms (GA), and simulated annealing (SA) are important AI techniques. Among these techniques, KBS is one of the most promising developments (Ismail et al. 1995). The KBS approach is being used in sheet metal industries for manufacturability assessment, process planning, strip-layout design, die design, die material selection, etc., Karima and Richardson (1987) conceptualized application of KBS in sheet metal forming industry. The system supports in converting the knowledge acquired from relevant sources into facts, procedures, judgment and control. Karima (1989) proposed a hybrid system for process planning in sheet metal forming. System considers the overall process of stamping engineering from the micro and the macro perspectives. Shpitalni and Saddan (1994) presented an application “BEND” of the graph search method for the generation of bending sequences. Lin and Chang (1996) developed an expert system for the selection of sheet metal bending tool. Ong et al. (1997) reported to develop a fuzzy set system to determine the sequence of bending operations in press brake machines. Gupta et al. (1998) proposed a process planning system for sheet metal parts. They applied a greedy algorithm to determine the bending sequence. Duflou et al. (1999) suggested a penalty function method and the traveling salesman problem method to determine bending sequences in press brake machines. Cakir et al. (2005) proposed an expert system for die and mold making operations. System requires the input from the user for part geometry and material, tool condition, and operation type. Kim et al. (2006) developed a fuzzy set theory method for determining the sequence of bending operations. Farsi and Arezoo (2009) proposed a procedure for bend sequencing determination with Fuzzy sets. Kumar and Singh (2011) developed an intelligent progressive die design system named as “INTPDIE” using KBS approach. Naranje and Kumar (2014) proposed a KBS for automatic design of deep drawing dies. Nasr et al. (2014) reported an expert system for design of sheet metal blanking dies.

The reviewed literature reveals the growing interest of worldwide researchers and technocrats in the area of computer aided die design for sheet metal work. Commercial CAD softwares being used in sheet metal industries assist die designer to reduce the design time to some extent and hence increase productivity. But these are unable to fully automate the die design process. Further, die designer needs to use multiple software packages for various activities of die design process and faces problems pertaining to nonexistence of connectivity between these softwares. Also these systems are costly and hence unaffordable for small scale industries, especially in developing countries. Further well trained, competent and experienced persons are required to operate these softwares and interpret the results. Some researchers have applied efforts to develop KBSs for die design. But very less effort is applied to automate the design of bending dies. Further, the systems reported in the literature for bending dies are not able to accomplish all design tasks and not fully automatic. Also domain experts are required to operate and accomplish the die design process.

The present chapter describes a KBS developed for automatic design of bending dies.

3 Proposed KBS for Automatic Design of Bending Dies

As the design task of bending die involves various activities, therefore, the proposed system namely ASDBD (*A*utomatic *S*ystem for *D*esign of *B*ending *D*ies) has been organized into various subsystems and modules as depicted in Fig. 3. The subsystems and modules are briefly described as under (Panghal and Kumar 2013).

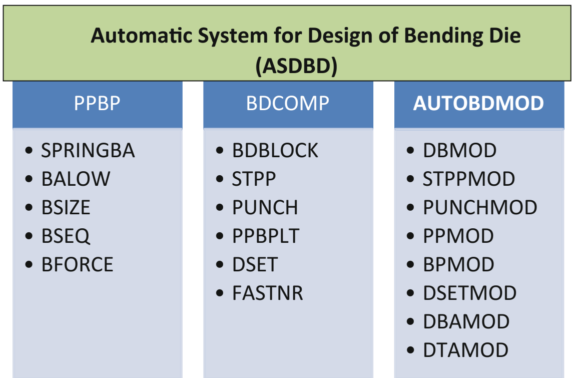


Fig. 3 Organization of the proposed system

3.1 Subsystem PPBP

The subsystem namely PPBP (*P*rocess *P*lanning of *B*ending *P*arts) is developed for process planning of sheet metal parts produced on bending die. System is structured in form of five modules as listed below.

(i) Module SPRINGBA for determination of springback angle,
(ii) Module BALOW for calculation of bend allowance,
(iii) Module BSIZE for determination of blank size,
(iv) Module BSEQ for determination of bending sequence, and
(v) Module BFORCE for calculation of bend force.

(i) Module SPRINGBA

This module is developed for determination of springback angle. The Springback angle depends on sheet material, sheet thickness, and bend radius (Boljanovic 2004). It decreases with decrease in bend radius, sheet thickness, hardness of sheet material, and bend angle. There are certain parameters like punch radius, die radius, and clearance between punch and die which are used to control springback angle. Most of the die designers in sheet metal industries determine springback angle using their own thumb rules. After detailed discussion with domain experts, production rules are framed to develop KBS module for determining springback angle. The knowledge base of this module consists of more than 200 production rules coded in VB 6.0 language. A sample of production rules incorporated in the module is given in Table 1. The execution of this module is shown in Fig. 4. Module takes its inputs automatically from part data files PART.DAT and FE.DAT (generated during execution of computer aided system for feature extraction as discussed in Chap. 3). Finally it displays springback angle and stores this output in a data file namely SBA.DAT.

(ii) Module BALOW

Bend allowance is length of arc of neutral axis of a bend angle (Fig. 5). For a larger bend radius neutral axis is located approximately at the half of sheet thickness of bending part. The die designer needs to determine bend allowance for bending parts before designing the die (Boljanovic 2004). The general equation for the bend allowance (B.A.) at the neutral axis is given as:

$$\text{B.A.} = \frac{\pi\varphi}{180} R_n \qquad (1)$$

where

φ = bend angle
R_n = bend allowance radius at neutral axis (Fig. 4)

Table 1 A sample of production rule for SPRINGBA

S. No.	IF	THEN
1	Material = Steel Annealed; and $R_f/t \leq 1$; and $1.5 <$ Sheet thickness in mm ≤ 2.0; and Bend angle $\leq 15°$	Springback angle $(\Delta\alpha) = 0.5°$
2	Material = Steel Annealed; and $R_f/t \leq 2$; and $1.5 <$ Sheet thickness in mm ≤ 2.0; and $15° \leq$ Bend angle $\leq 30°$	Springback angle $(\Delta\alpha) = 0.7°$
3	Material = Steel Low Carbon Hardened; and $R_f/t \leq 2$; and $1.0 <$ Sheet thickness in mm ≤ 1.5; and $45° \leq$ Bend angle $(\varphi_f) \leq 60°$	Springback angle $(\Delta\alpha) = 2.2°$
4	Material = Steel Low Carbon Hardened; and $R_f/t \leq 2$; and $1.0 <$ Sheet thickness in mm ≤ 1.5; and $60° \leq$ Bend angle $(\varphi_f) \leq 90°$	Springback angle $(\Delta\alpha) = 2.7°$
5	Material = Cu (ETP); and $R_f/t \leq 2$; and $2.0 \leq$ Sheet thickness in mm ≤ 2.0; and Bend angle $(\varphi_f) \leq 15°$	Springback angle $(\Delta\alpha) = 0.75°$
6	Material = Cu (ETP); and $R_f/t \leq 2$; and $2.0 \leq$ Sheet thickness in mm ≤ 2.0; and $15° <$ Bend angle $(\varphi_f) \leq 30°$	Springback angle $(\Delta\alpha) = 1.0°$
7	Material = Cu (ETP); and $R_f/t \leq 2$; and $2.0 \leq$ Sheet thickness in mm ≤ 2.0; and $30° <$ Bend angle $(\varphi_f) \leq 45°$	Springback angle $(\Delta\alpha) = 1.3°$

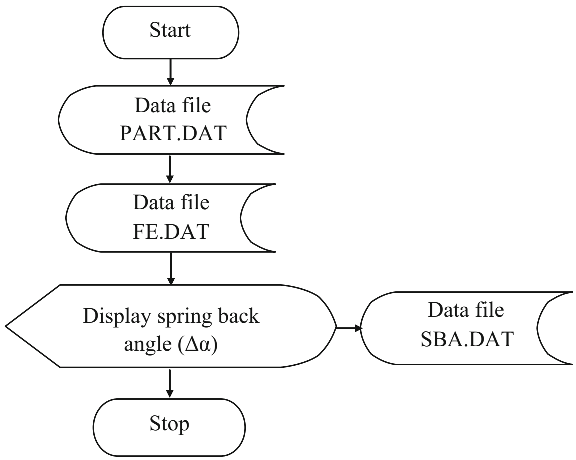


Fig. 4 Execution of module SPRINGBA

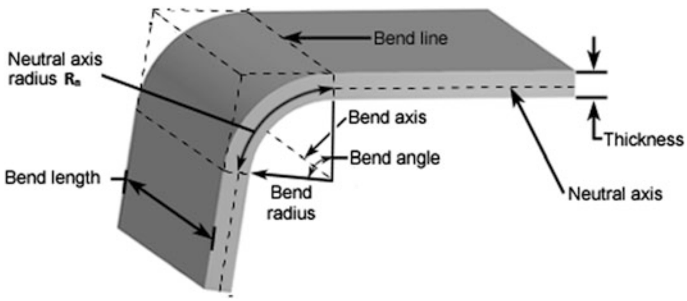


Fig. 5 Bend terminology

$$\text{Bend allowance radius}(R_n) = \xi \times t + R_i \tag{2}$$

where

ξ = bend factor
R_i = inner radius

Therefore, from Eqs. (1) and (2),

$$\text{B.A.} = \frac{\pi\varphi}{180}(\xi t + R_i) \tag{3}$$

The value of bend factor (ξ) corresponding to R_i/t ratio is given in Table 2 (Boljanovic 2004).

In the proposed system, a data base file for values of 'ξ' with respect to R_i/t ratio is constructed to determine bend allowance. The execution of the module BALOW is shown in Fig. 6. The module recalls the data file FE.DAT (as discussed in Chap. 3) to read sheet thickness. Then the system searches the value of ξ corresponding to R_i/t ratio in the data file. The intermediate values of 'ξ', which are not available in the database are determined by interpolation method. Finally, the system calculates bend allowance and displays it for the user. The value of bend allowance is stored automatically in a data file namely BALOW.DAT which is used further for determining blank size.

(iii) Module BSIZE

Blank size of a bending part depends on part shape (bend width, length of legs, bend angle, and bend radius) and bend allowance. A module namely BSIZE is developed for determination of blank size of part. Execution of the proposed module is depicted in Fig. 7. The module recalls data file FE.DAT, to read part

Table 2 Values of ξ corresponding to R_i/t

R_i/t	00.1	00.2	00.3	00.4	00.5	00.8	11.0	11.5	22.0	33.0	44.0	55.0	110.0
ξ	00.23	00.29	00.32	00.35	00.37	00.40	00.41	00.44	00.45	00.46	00.47	00.48	00.5

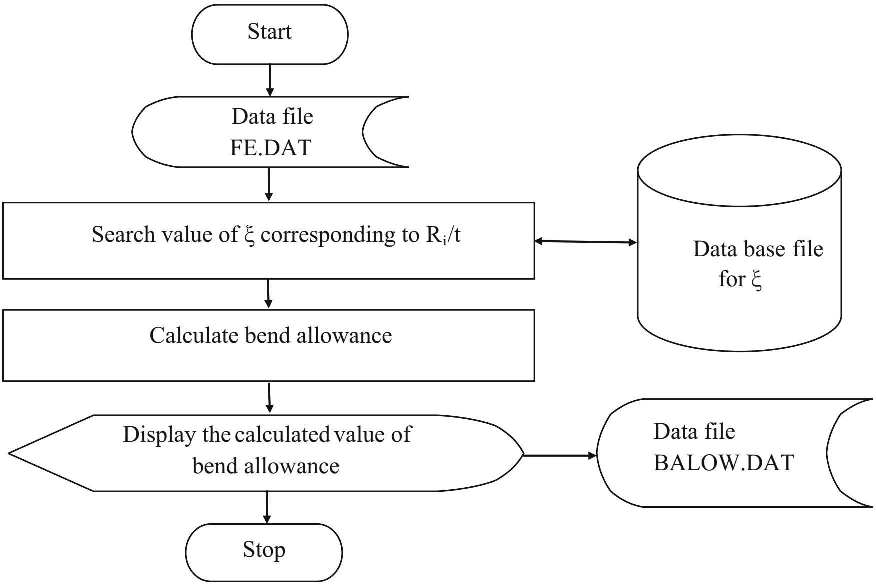


Fig. 6 Execution of module BALOW

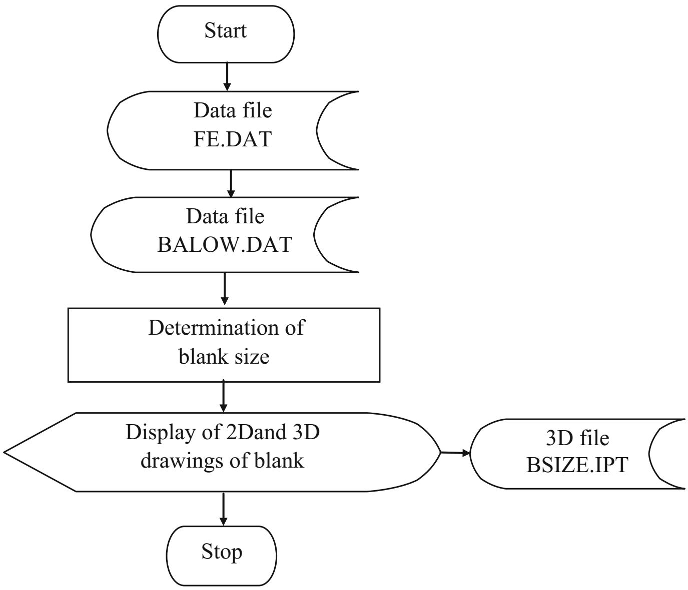


Fig. 7 Execution of module BSIZE

detail. Bend allowance is taken from the data file BALOW.DAT generated during execution of previous module. Next, module unfolds all bends one by one using built-in API (application programming interface) namely 'UNFOLD' of Inventor software for determination of blank size. This API uses the matrix transformation approach for unfolding the bends. Finally module displays the three-dimensional (3-D) and two-dimensional (2-D) drawings of blank of bending part for the user. The 3-D drawing of blank is stored in a drawing file labeled as BSIZE.IPT.

(iv) Module BSEQ

For determination of bending sequence, a module namely BSEQ (*B*ending *Seq*uence) is developed (Panghal et al. 2016). There are certain process variables like bend angle, position of a bend, angle with feed direction, etc., that play a vital role in deciding bend sequence. By considering these parameters, a procedure is developed to determine the bend sequence of a complex bending part. The steps to determine bend sequence are briefly described as under.

(a) Identification of base/mother plane

The base plane is most important plane in a bending part. All the bends are formed around it as it remains stationary during bending operation. Base plane is identified on the basis of following criteria:

- It must be centrally located, i.e., base plane must be surrounded by maximum number of bends, and It must be the largest plane.
- If more than one plane qualifies on the basis of above criteria, then selection of base plane is done on the basis of minimum distance between the centers of plane to the farthest bend axis among the qualifying planes.

To implement the above criteria, all planes of bending part are sorted area wise. The plane of highest area is awarded highest marks (i.e., 100 marks) and other planes are awarded marks as per their proportionate area with reference to the plane having highest marks. Thereafter, the planes are sorted as per number of surrounding planes. The plane with highest number of surrounded planes is awarded highest marks and other planes are awarded marks as per their proportionate number of surrounding planes. The plane having highest total marks (i.e., out of 200 marks) awarded as per the above two criteria is selected as base/mother plane. In case of tie of marks among the planes, then selection of base plane is done on the basis of minimum distance between the centers of plane to the farthest bend axis among the qualifying planes. The proposed procedure for identification of base plane is shown in Fig. 8.

(b) Categorization of Bends

Bends are required to be categorized in such a manner that they have highest probability of getting grouped together. Feed direction plays a vital role in categorization of bends. Bends can be categorized on the basis of bend axis position with reference to the feed direction, i.e., parallel, perpendicular, or inclined.

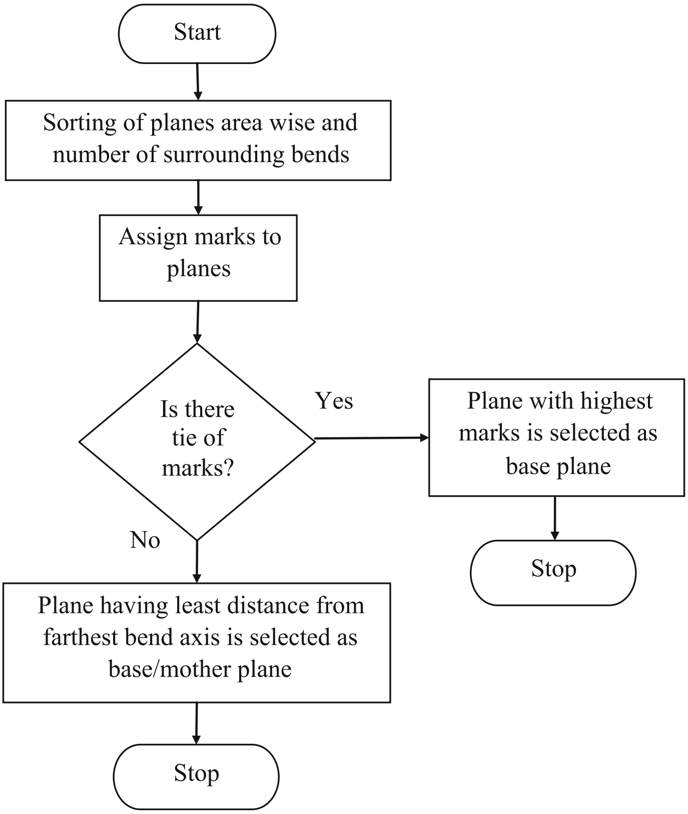
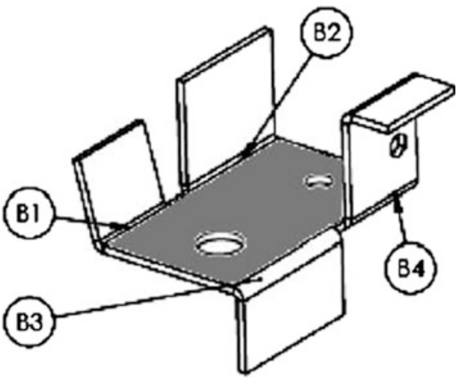


Fig. 8 Procedure for selection of base/mother plane

Fig. 9 A typical bending part (illustration of rule 1)



(c) Grouping of Bends

The bends from each category is required to be grouped together. The purpose of the grouping is to identify the bends which can be formed together. There are many

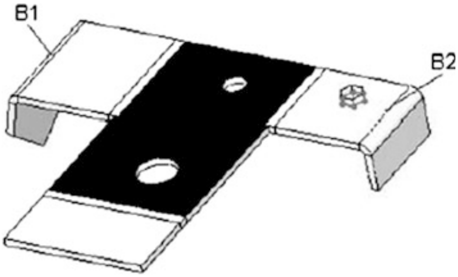


Fig. 10 A typical bending part (illustration of rule 2)

variables on the basis of which bends can be grouped together. After detailed discussion with the domain experts and review of published literature, the following rules have been identified which have much impact on grouping of bends.

Rule1: Bends whose bend axis is coplanar and having the same direction (either up or down) can be grouped in the same group.

For example, in a typical bending part shown in Fig. 9 bends B1 and B2 are grouped in same group.

Rule 2: Bends that are equal number of bends away from the base plane and also have the same direction (either up or down) can be grouped in the same group.

For example, in a typical bending part as shown in Fig. 10, bends B1 and B2 should be grouped in the same group.

The above two rules are applied to all categories of bends individually. The procedure for grouping of bends is shown in Fig. 11.

(d) Prioritization of Bend Groups

There are number of variables that contribute in prioritization of groups. On reviewing published literature and detailed discussion with domain experts, the rules that are most significant in deciding the prioritization of groups are identified. All these rules do not have equal impact on deciding the sequence of groups. A significance factor for each rule is identified. The groups are awarded marks as per rules and further multiplied by individual significance factor. The total marks for individual groups are calculated. The groups are further sorted in descending order as per total marks obtained to decide the sequence of groups. The rules with their significance factor are tabulated in Table 3.

The above procedure is coded in VB 6.0 programing language. User can interact with the system through GUI. The system is parametric and automatic in nature. Execution of the proposed module is depicted in Fig. 12. The module reads 3-D drawing of blank from the file BSIZE.IPT generated during execution of BSIZE module. The module also recalls data file FE.DAT to take inputs such as sheet thickness, number of bends, bend angle, and bend direction. Thereafter, module sequentially performs the activities includes identification of base plane, bend categorisation, bend grouping, bend group prioritization, and finally displays the bending sequence through 3-D drawings of bending part. The output of the module in form of group sequence (along with detail of bends in each group) is stored in a data file namely BSEQ.DAT.

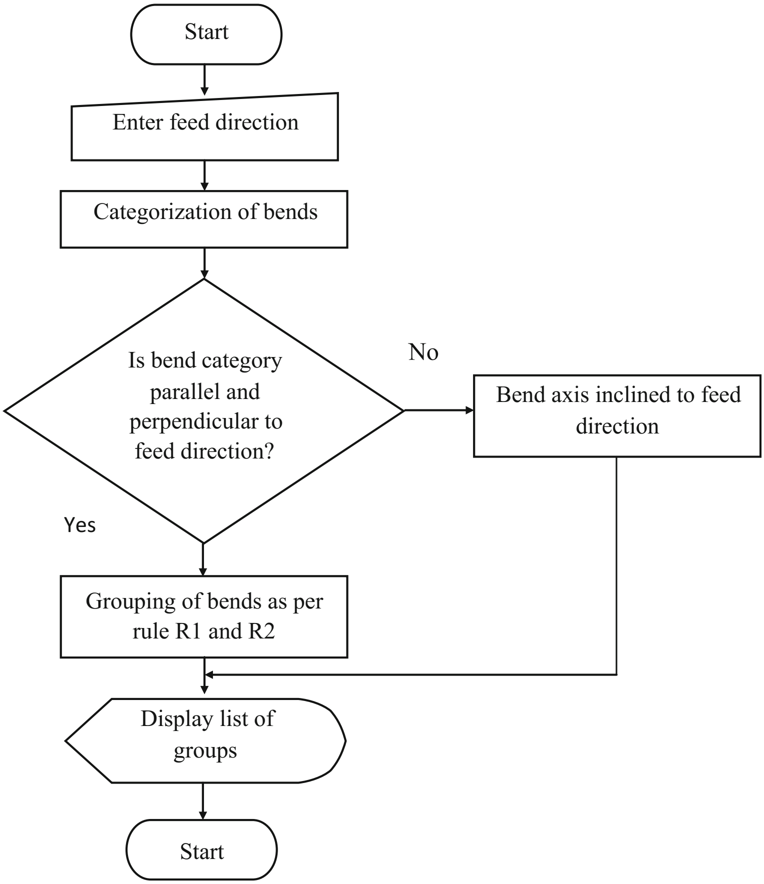


Fig. 11 Procedure for grouping of bends

Table 3 Rules for deciding prioritization of groups

Rule	Description	Significance factor
R1	The distance in terms of number of planes in between a bend and base plane have the maximum impact on bend sequencing. Bend having maximum number of planes away from the base plane should be addressed earlier	0.6
R2	The group having more number of bends, later it should be addressed	0.4
R3	The bend angle more than 90° should be addressed in two stages	0.3
R4	The bends that has perpendicular bend axis to feed direction should be addressed first. Thereafter, inclined and in the last bend with parallel bend axis should be considered	0.1

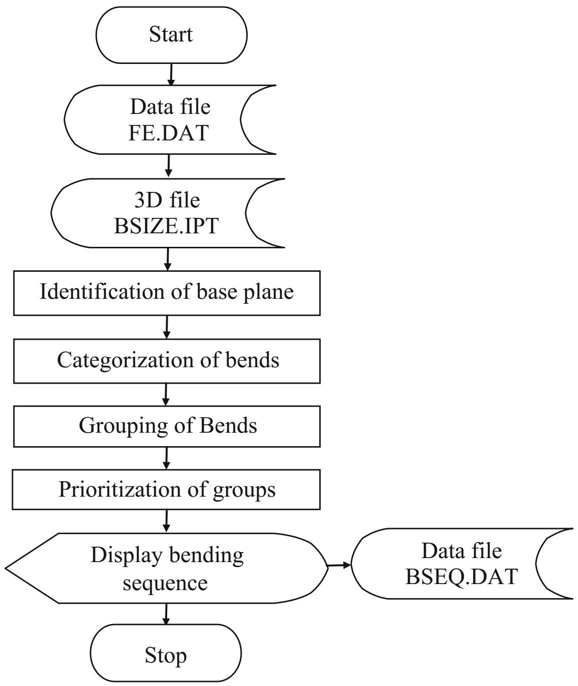


Fig. 12 Execution of module BSEQ

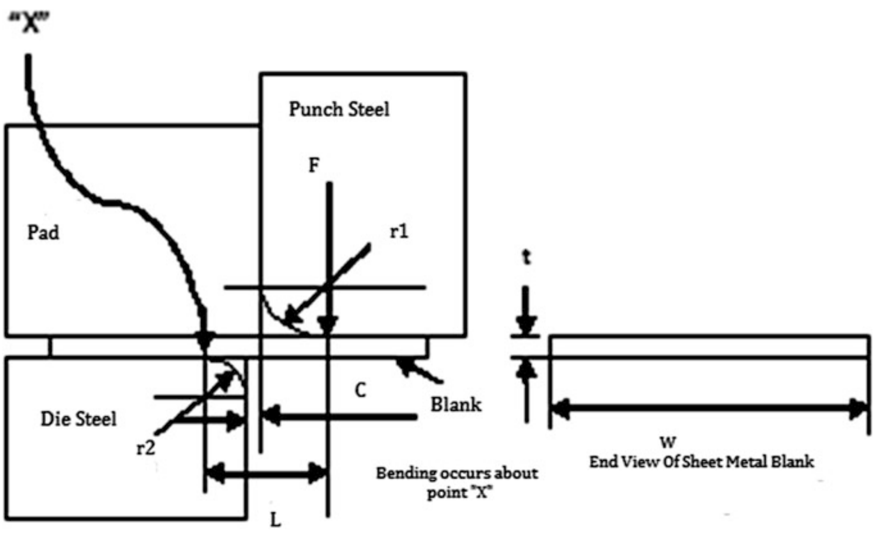


Fig. 13 Schematic diagram for bending force calculation (Boljanovic 2004)

(v) Module BFORCE

Bending force depends on the strength of sheet material, size and thickness of bending part, and clearance between punch and die. Bending force is required to be calculated for different types of bends. A schematic diagram for bending force calculation is depicted in Fig. 13.

The formula used for force calculation is as follows:

$$\text{Force}(F) = K \times Swt^2/L \quad (4)$$

where

K bend Constant (values are listed in Table 4)
S Ultimate tensile strength of material
w Sheet metal width at bend
t Sheet thickness

$$L = r_1 + c + r_2 \quad (5)$$

where

r_1 punch corner radius
c die clearance
r_2 die corner radius

Table 4 Value of constant *K* (Boljanovic 2004)

S. No.	Bending type	*K*
1	Wiping	0.333
2	U-die	0.667
3	V-die	1.33

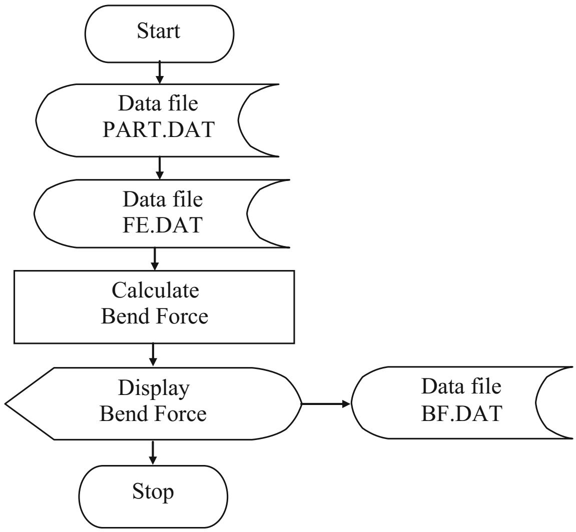


Fig. 14 Execution of module BFORCE

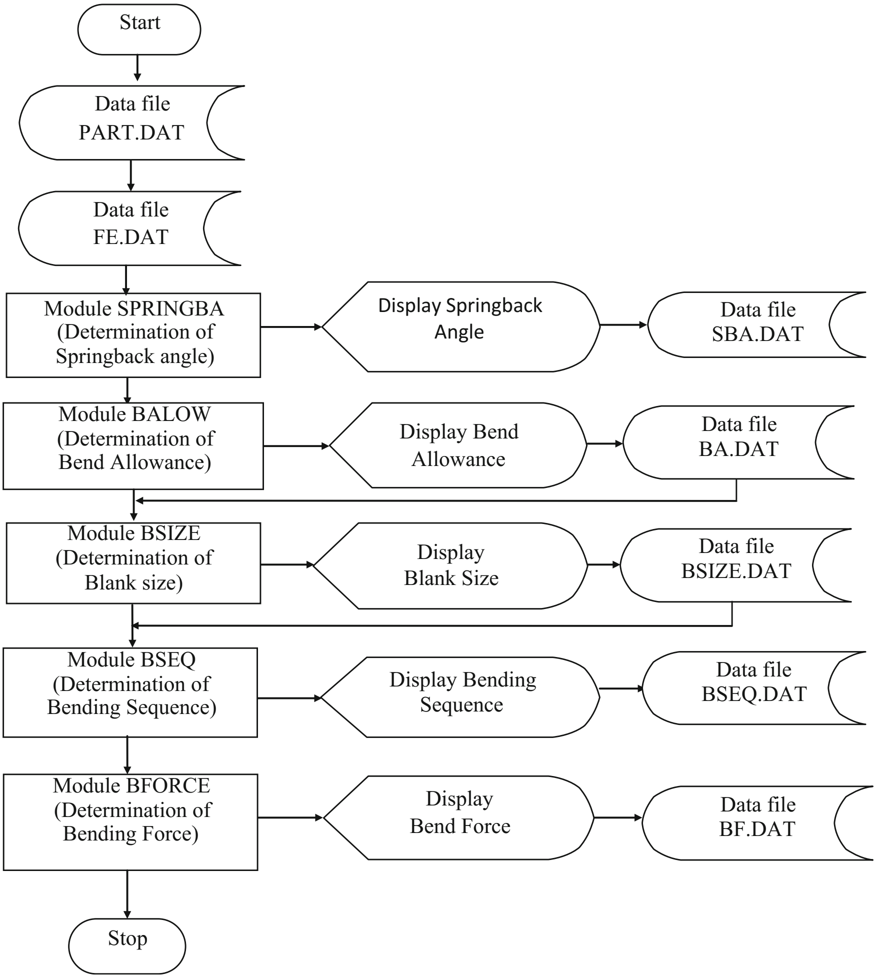


Fig. 15 Execution of subsystem PPBP

A module namely BFORCE is developed to calculate the bend force required to bend a part. The execution of this module is shown in Fig. 14. Module BFORCE reads essential input data from data files PART.DAT and FE.DAT. Then the module calculates the bend force and displays it for the user.

The Execution of subsystem PPBP is shown in Fig. 15. System initially takes input from PART.DAT file. Further, the required inputs related to design features of bending part are taken from another data file namely FE.DAT. The output of SPRINGBA module in the form of springback angle is stored in the data file namely SBA.DAT. The module namely BALOW is capable to determine bend allowance for all bend and the output of it is stored in the data file BA.DAT. The next module namely BSIZE is developed for determination of blank size of bend part. Bend allowance is taken from the data file BA.DAT generated during execution of previous module. The module recalls a built-in API (application programming interface) namely "UNFOLD" of Inventor software for determination of blank size. This API uses the matrix transformation approach for unfolding the bends. Finally module displays the three-dimensional (3-D) and two-dimensional (2-D) drawings of blank of bending part for the user. The outputs of the module stores in data file BSIZE.DAT. Next module namely BSEQ is used to determine the bend sequencing of bend part. The module reads 3-D drawing of blank from the file BSIZE.DAT generated during execution of BSIZE module. The module also recalls data file FE.DAT to take inputs such as sheet thickness, number of bends, bend angle, and bend direction. Thereafter module sequentially performs the activities including identification of base plane, bends categorization, bend grouping, bend group prioritization, and finally displays the bending sequence through 3-D drawings of bending part. The output of the module in form of group sequence (along with detail of bends in each group) is stored in a data file namely BSEQ. DAT. Finally, a module namely BFORCE is developed for determining the bend force. A module namely BFORCE developed to calculate the bend force required to bend a part. Module BFORCE reads essential input data from data files PART.DAT and BFE.DAT. The module calculates the bend force and displays it for the user.

3.2 Subsystem BDCOMP

A subsystem namely BDCOMP(*B*ending *D*ie *Comp*onents) is developed for selection of type and size of bending die components. It is structured in form of six KBS modules namely:

(i) Module BDBLOCK for selection of die block,
(ii) Module STPP for selection of stripper plate/pressure plate,
(iii) Module PUNCH for selection of punch(es),
(iv) Module PPBPLT for selection of punch plate and back plate,
(v) Module DSET for selection of die-set, and
(vi) Module FASTNR for selection of fasteners (bolts and dowels).

The knowledge base of proposed subsystem consists of more than 700 production rules coded in VB 6.0 language. A sample of production rules is given in Table 5. Execution of the system is shown in Fig. 16. For required inputs, the system reads data files PART.DAT and BSEQ.DAT generated during execution of process planning subsystem. Various modules of the system impart expert advices for selection of bending die components including die block, stripper plate/pressure plate, punch(es), punch plate, back plate, die-set, and fasteners. The module namely BDBLOCK imparts expert advice on the selection of die block. The outputs of modules are stored in different data files which can be recalled for automatic die modeling.

Table 5 A sample of production rules incorporated in subsystem BDCOMP

1	Sheet thickness (mm) > 0.5; and Sheet thickness (mm) ≤ 1.6; and Die material = Tool steel [SERVERKER 21]	Select die block thickness (mm) = 24.0
2	Sheet thickness (mm) > 1.6; and Sheet thickness (mm) ≤ 3.2; and Die material = Tool steel [SERVERKER 21]	Select die block thickness (mm) = 29.0
3	Sheet thickness in mm > 3.2; and Sheet thickness in mm ≤ 4.5; and Die material = Tool steel [SERVERKER 21]	Select thickness of die block (mm) = 35.0
4	Size of blank length (mm) ≥ 150.0; and Size of blank length (mm) ≤ 280; and Sheet thickness (mm) ≥ 6.4; and Die material = Tool steel [SERVERKER 21]	Select width of die block (mm) = (blank width + 72.0); and Select length of die block (mm) = (blank length + 100.0)
5	Type of the die = wiping; and Sheet thickness in mm > 2.5; and Sheet thickness in mm ≤ 3.0; and Bending force ≤100,000 N	Select stripper plate thickness in mm = 25; Width and length of stripper plate in mm = length and width of die block; and Select four medium pressure springs with 50 % deflection; free length of each spring in mm = 25; preload of spring in mm = 3.75; outer diameter of spring in mm = 12.0
6	Type of the die = wiping; and Sheet thickness in mm ≥ 3.0; and Bending force ≤100,000 N	Select stripper plate thickness in mm = 28; Width and length of stripper plate in mm = length and width of die block; and Select four medium pressure springs with 50 % deflection; free length of each spring in mm = 25; preload of spring in mm = 3.75; outer diameter of spring in mm = 12.0
7	Type of die = wiping die; and Sheet thickness in mm > 2.5; and Sheet thickness in mm ≤ 3; and Bending force > 10,000 N; and Bending force ≤ 15,000	Select punch type = wiping; and Punch length in mm = 70; and Punch width in mm = (bend width + 4.0); and Punch thickness in mm = 30; and Punch corner radius in mm = two times of sheet thickness
8	Type of die = wiping die; and Sheet thickness in mm > 2.5; and Sheet thickness in mm ≤ 3; and Bending force > 15,000 N	Select punch type = wiping; and Punch length in mm = 70; and Punch width in mm = (bend width + 4.0); and Punch thickness in mm = 40; and Punch corner radius in mm = two times of sheet thickness
9	Punch thickness in mm > 30; and Sheet material = steel annealed hardened	Select thickness of punch plate in mm = 30; and Length of punch plate = die block length; and Width of punch plate = die block width

(continued)

Table 5 (continued)

10	Sheet thickness in mm < 3.0; and Sheet material = steel annealed hardened	Select thickness of back plate in mm = 9.5; and Back plate length = die block length; and Back plate width = die block width
11	Production quantity > 30,000; and Production quantity ≤ 45,000; and Length of die in mm > 200; and Length of die in mm ≤ 250; and Width of die in mm > 80; and Width of die in mm ≤ 100; and Dimensional tolerance in mm < 0.1	Select center pillar die-set with dimensions in mm as: Thickness of punch holder plate = 25; Thickness of die holder plate = 32; Diameter of pillar = 32; Length of die-set = (length of die + 140); Width of die-set = (width of die +140); and Shank diameter = 24
12	Production quantity > 30,000; and Production quantity ≤ 45,000; and Length of die in mm > 250; and Length of die in mm ≤ 315; and Width of die in mm > 100; and Width of die in mm≤ 125; and Dimensional tolerance in mm < 0.1	Select center pillar die-set with dimensions in mm as - Thickness of punch holder plate = 32; Thickness of die holder plate = 40; Diameter of pillar = 32; Length of die-set = (length of die + 140); Width of die-set = (width of die +140); and Shank diameter = 24
13	Die area > 5000.0 mm^2; and Die area ≤ 10,000.0 mm^2; and Bending force ≤ 50T	Use four Allen bolts of size M6 and two dowels of diameter 6 mm
14	Die area > 10,000.0 mm^2; and Die area ≤ 15,000.0 mm^2; and Bending force ≤ 50T	Use four Allen bolts of size M8 and two dowels of diameter 8 mm

3.3 Subsystem AUTOBDMOD

A subsystem labeled as AUTOBDMOD (*Auto*matic *B*ending *D*ie *Mod*eling) is developed for automatic modeling of die components and die assembly of bending die. This system works in conjunction with KBS modules developed for selection of die components of bending die. The outputs of various modules of subsystem BDCOMP are stored in different data files. These data files are recalled automatically for die modeling. The users need not to enter any input to the system. For development of the proposed subsystem, Visual Basic (VB 6.0) program is written to invoke commands of Inventor software such as EXTRUDE, DRAFT, CHAMFER, etc., for 3-D modeling of die components and die assembly. To generate 2-D drawings, a computer code in VB 6.0 language is written to open 3-D files into drawing view of Inventor software. The developed computer code also ensures the proper scaling and automatic dimensioning of 2-D drawings. Graphic user interface (GUI) of the proposed system is developed using VB 6.0 and is interfaced with Inventor software. The subsystem AUTOBDMOD is structured into eight modules namely:

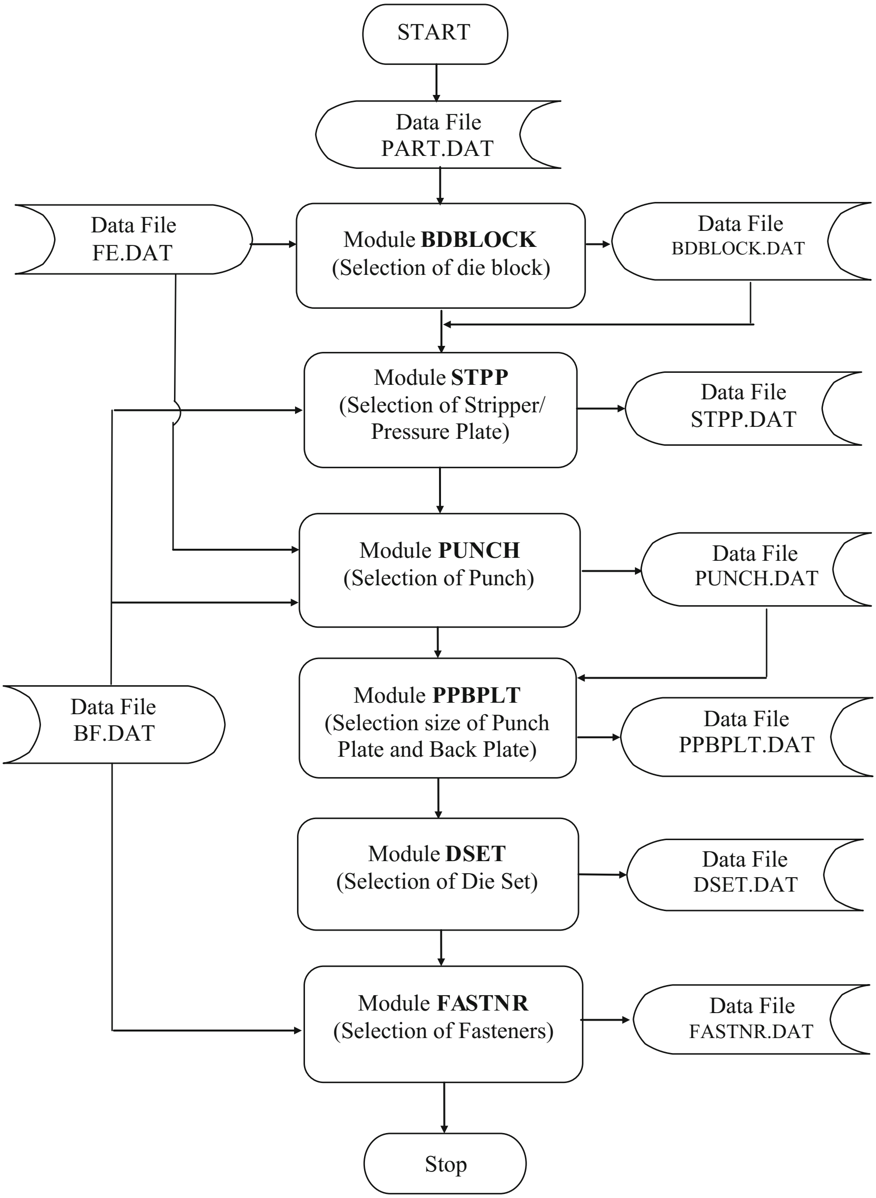


Fig. 16 Execution of system BDCOMP

(i) Module DBMOD for modeling of die block,
(ii) Module STPPMOD for modeling of stripper plate and pressure plate,
(iii) Module PUNCHMOD for modeling of punch(es),
(iv) Module PPMOD for modeling of punch plate,
(v) Module BPMOD for modeling of back plate,
(vi) Module DSMOD for modeling of die-set,
(vii) Module DBAMOD for modeling of die bottom assembly, and
(viii) Module DTAMOD for modeling of die top assembly.

Execution of the proposed subsystem AUTOBDMOD is shown in Fig. 17. The first module namely BDMOD is developed for automatic modeling of die block of bending die. This module takes required inputs from data files DBLOCK.DAT and FASTNR.DAT generated during the execution of KBS modules developed respectively for selection of die block and fasteners. Finally, the module generates 2-D and 3-D drawings of die block in the drawing editor of Inventor software. 3-D drawing is saved automatically as a global block namely GDBMOD. The next module labeled as STPPMOD is constructed for automatic modeling of stripper plate/pressure plate. Inputs in form of size of stripper plate/pressure plate and fasteners are read automatically from the data files namely STPP.DAT and FASTNR.DAT generated during execution of previously developed KBS modules of subsystem BDCOMP. Finally, the module generates 2-D and 3-D drawings of stripper plate/pressure plate. The output in form of 3-D drawing is stored automatically in a global block namely GSTPPMOD. The module namely PUNCHMOD is developed for automatic modeling of punch(es) of bending die. The module takes input automatically from data file PUNCH.DAT. The module generates 2-D and 3-D drawing of punch(s). The 3-D drawing is saved automatically as global block namely GPUNCHMOD. The module labeled as PPMOD is developed to generate drawings of punch plate of bending die. The module takes inputs in the form of size of punch plate from the data file PPBLT.DAT and number and size of fasteners from the data file FASTNR.DAT. Output in form of 3-D drawing of punch plate is saved as a global block namely GPPMOD. The module namely BPMOD takes required inputs from data files PPBLT.DAT and FASTNR.DAT. Finally it generates 3-D and 2-D drawings of back plate. The 3-D drawing of back plate is automatically saved as a global block namely GBPMOD. The module DSMOD is constructed for modeling of die-set of bending die. The module takes required input from data file DSET.DAT and FASTNR.DAT. The 3-D drawing of die-set is automatically saved as global block namely GDSETMOD. The modules labeled as DBAMOD and DTAMOD are developed, respectively for automatic modeling of bottom die assembly and top die assembly of bending die. Bottom die assembly consists of die holder plate of die-set, die block, and pressure plate (in case of U-die only). Top die assembly is a unit of punch holder plate of die-set, back plate, punch plate, punch(es) and stripper plate. The proposed modules compute reference point on die-set for inserting global blocks of respective die components to generate 3-D drawings of bottom die assembly and top die assembly. The 2-D drawings are generated automatically from 3-D files.

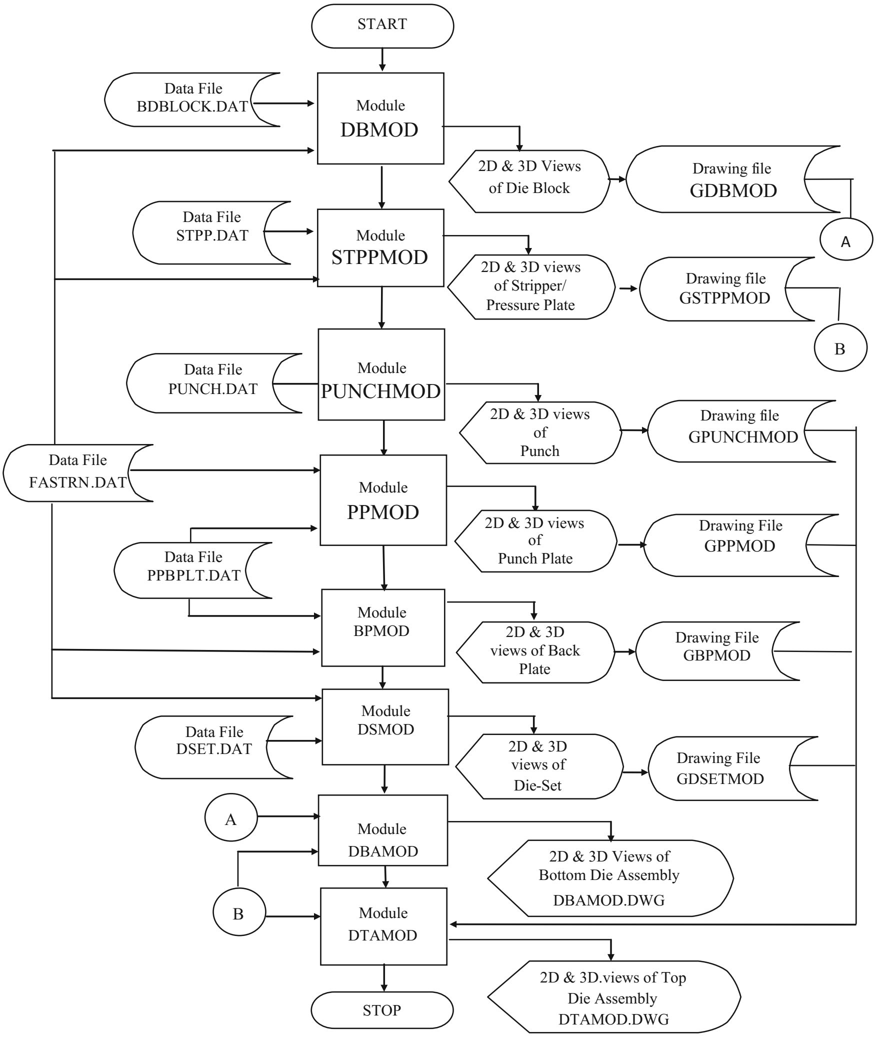
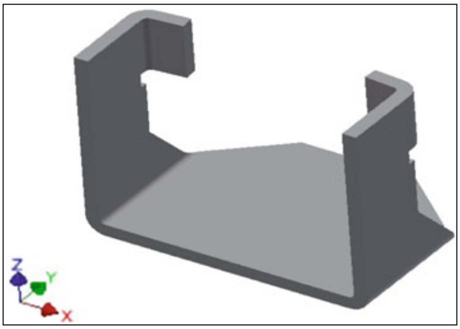


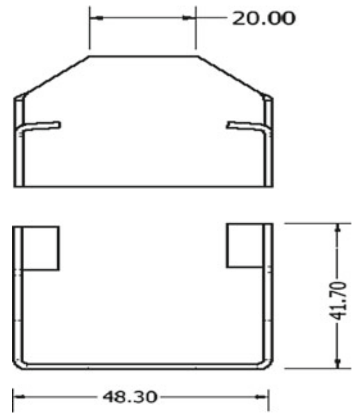
Fig. 17 Execution of the proposed system AUTOBDMOD

4 Validation of System ASDBD

The developed system ASDBD has been tested successfully for different sheet metal parts taken from stamping industries. A sample run of the system for one sheet metal part (Fig. 18) of stamping industry namely M/s Kochar Agro Industries Pvt. Ltd.



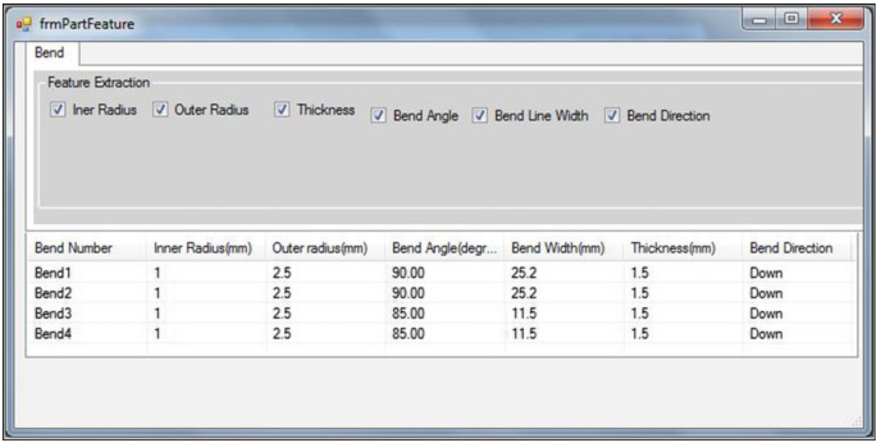
(a) 3-D view



(b) 2-D view

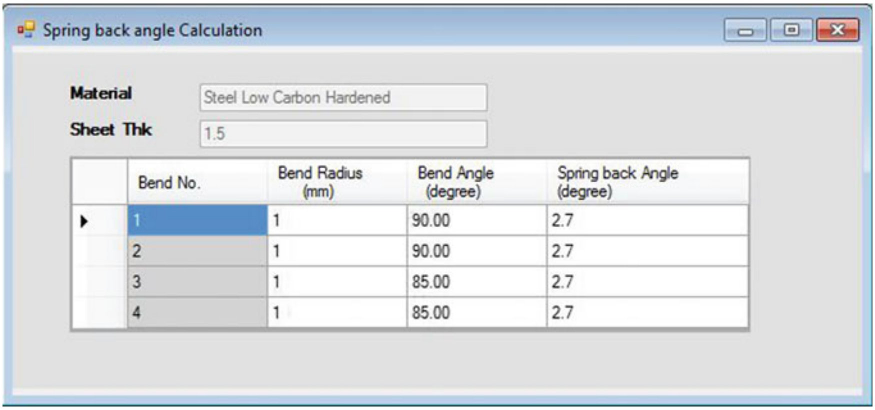
Fig. 18 Example part (material = low carbon steel hardened, sheet thickness = 1.5 mm, all dimensions are in mm)

Faridabad, India is depicted in Figs. 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58 and 59. The recommendations obtained by the system were found very similar to those actually used in the sheet metal industries for the example part. In sheet metal industries, experienced die designers use various commercial CAD softwares for drafting of die components. These softwares are not only costly (cost of a single software is more than 4 Lakhs Indian Rupees) but also not capable to automate die design process. Highly experienced persons are required to accomplish all tasks of die design. The developed system executes the tedious task of design of bending die in less than an hour and gives final outputs in form of drawings of die components and die assembly which can be used directly for die manufacturing.



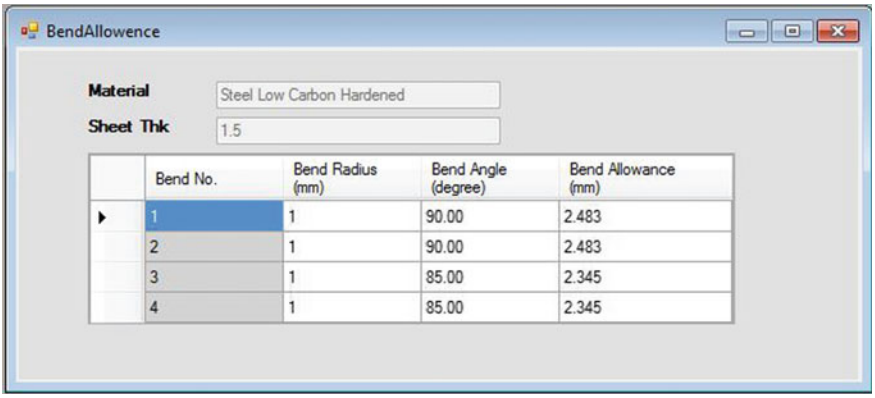
Bend Number	Inner Radius(mm)	Outer radius(mm)	Bend Angle(degr...	Bend Width(mm)	Thickness(mm)	Bend Direction
Bend1	1	2.5	90.00	25.2	1.5	Down
Bend2	1	2.5	90.00	25.2	1.5	Down
Bend3	1	2.5	85.00	11.5	1.5	Down
Bend4	1	2.5	85.00	11.5	1.5	Down

Fig. 19 Output of BFE system



Bend No.	Bend Radius (mm)	Bend Angle (degree)	Spring back Angle (degree)
1	1	90.00	2.7
2	1	90.00	2.7
3	1	85.00	2.7
4	1	85.00	2.7

Fig. 20 Output of module SPRINGBA



Bend No.	Bend Radius (mm)	Bend Angle (degree)	Bend Allowance (mm)
1	1	90.00	2.483
2	1	90.00	2.483
3	1	85.00	2.345
4	1	85.00	2.345

Fig. 21 Output of module BALOW

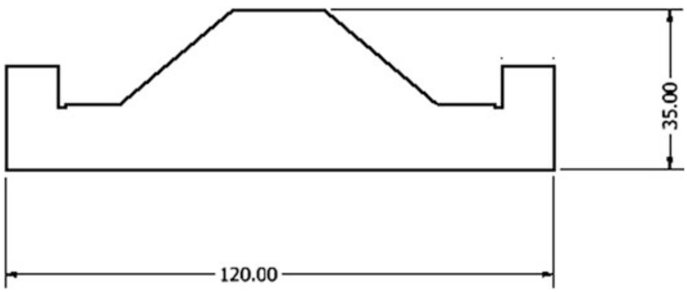


Fig. 22 Output of module BSIZE

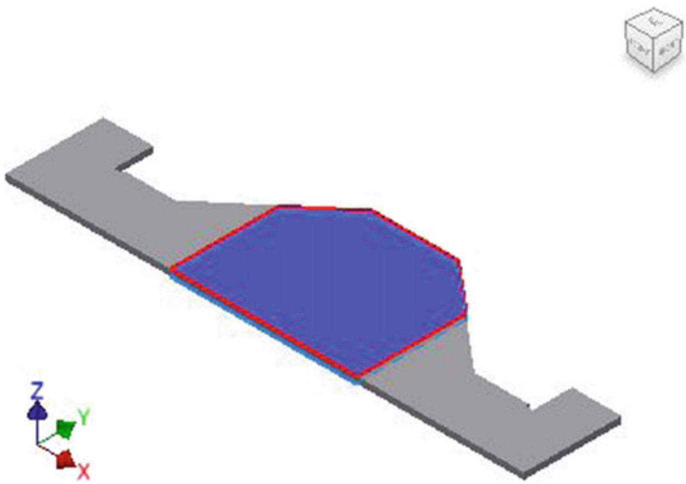


Fig. 23 Mother/base plane selection

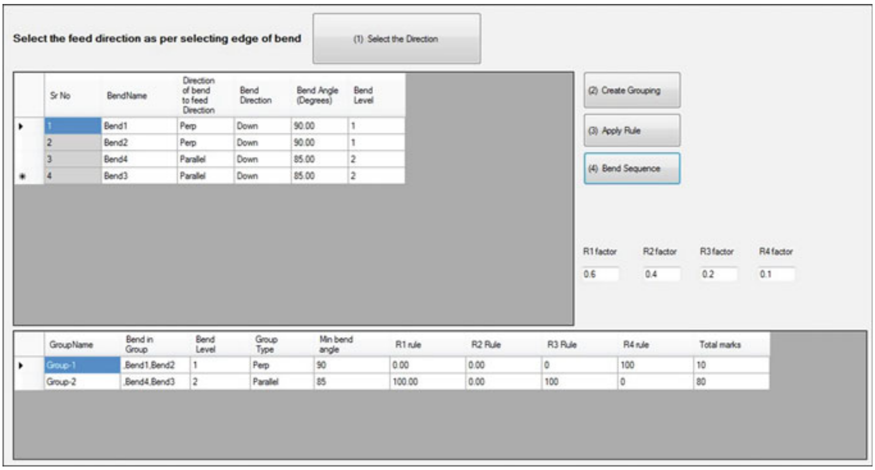
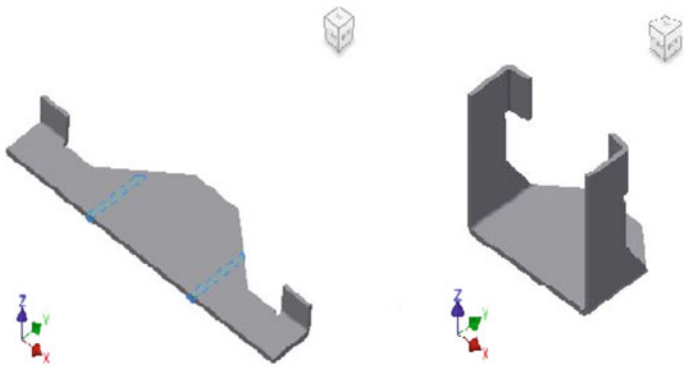
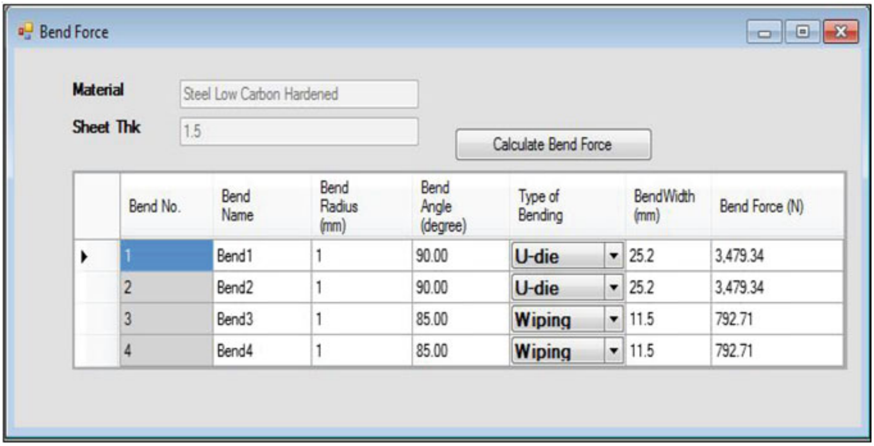


Fig. 24 Output of module BSEQ



(a) Stage 1 **(b)** Stage 2

Fig. 25 Bending sequence



Bend No.	Bend Name	Bend Radius (mm)	Bend Angle (degree)	Type of Bending	BendWidth (mm)	Bend Force (N)
1	Bend1	1	90.00	U-die	25.2	3,479.34
2	Bend2	1	90.00	U-die	25.2	3,479.34
3	Bend3	1	85.00	Wiping	11.5	792.71
4	Bend4	1	85.00	Wiping	11.5	792.71

Fig. 26 Output of module BFORCE

Even a novice can perform the die design using this system. Therefore, it eliminates dependency on domain experts. The system is implemented on a PC having Inventor software (Cost is approximately 3 Lakhs Indian Rupees). Therefore, its low cost of implementation makes it affordable even for small scale industries.

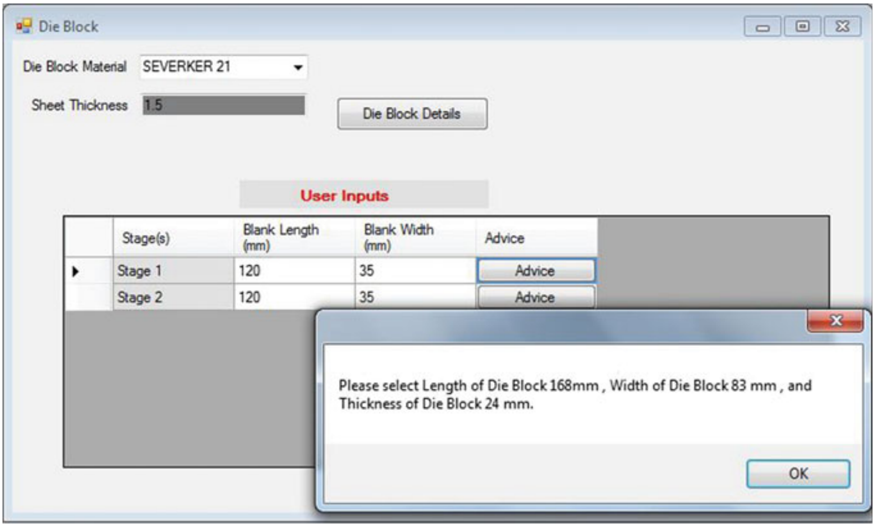


Fig. 27 Output of module BDBLOCKfor die block (stage 1)

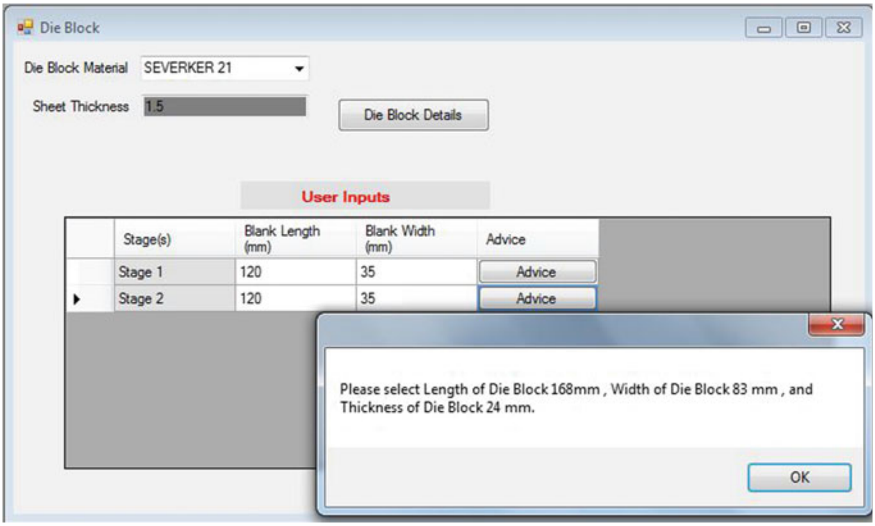


Fig. 28 Output of module BDBLOCKfor die block (stage 2)

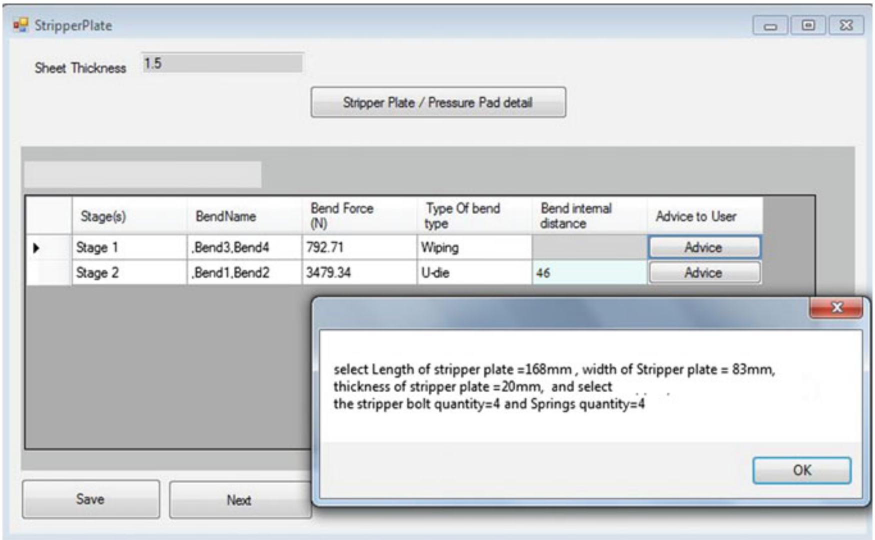


Fig. 29 Output of module STPP for stripper plate (stage 1)

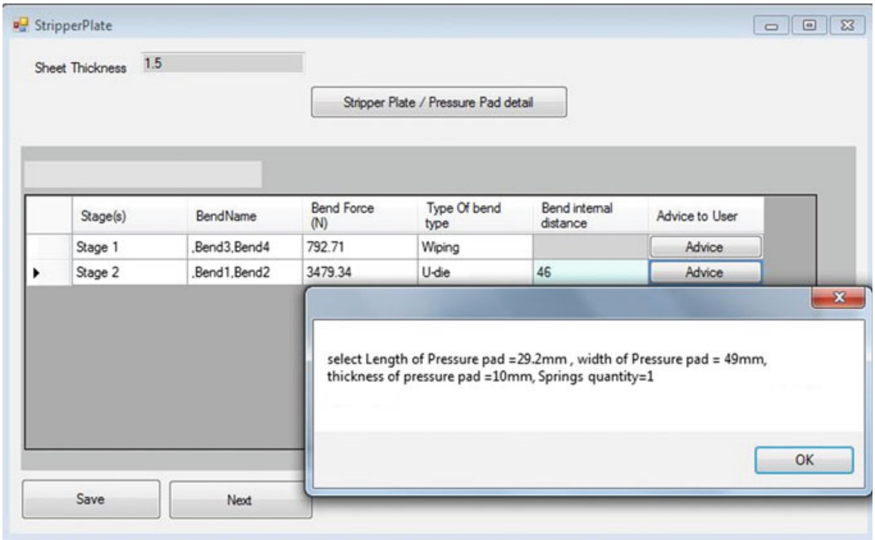


Fig. 30 Output of module STPP for pressure plate (stage 2)

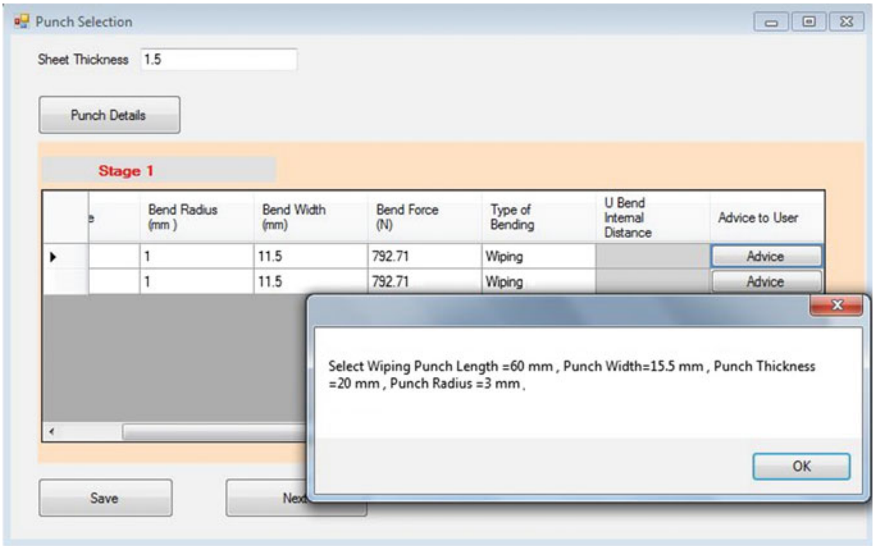


Fig. 31 Output of module PUNCH for punch (stage 1)

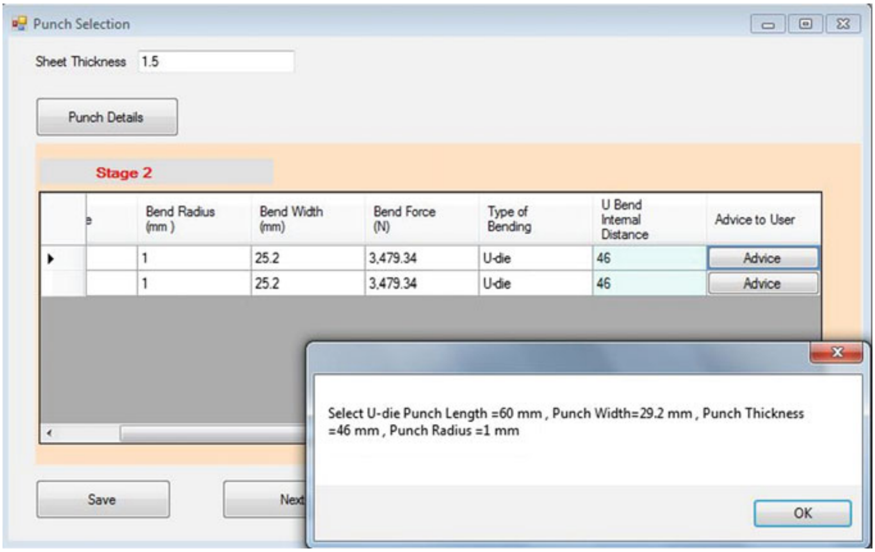


Fig. 32 Output of module PUNCH for punch (stage 2)

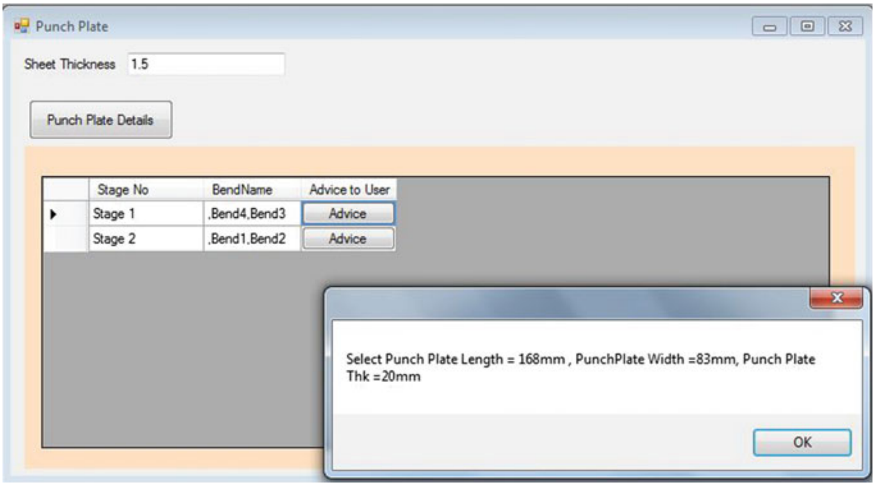


Fig. 33 Output of module PPBPLT for punch plate (stage 1)

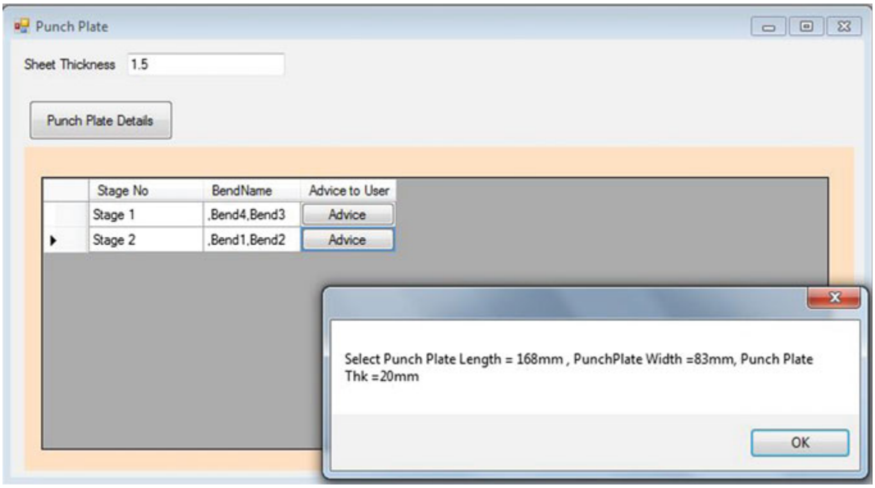


Fig. 34 Output of module PPBPLT for punch plate (stage 2)

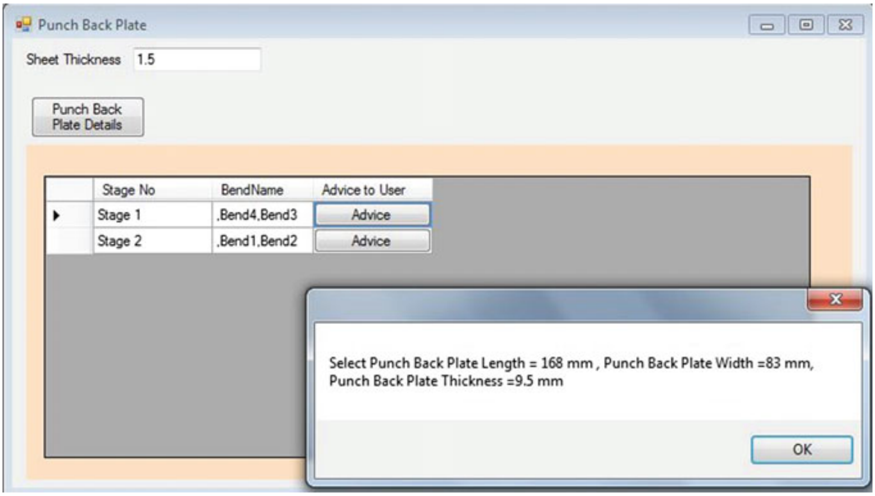


Fig. 35 Output of module PPBPLT for back plate (stage 1)

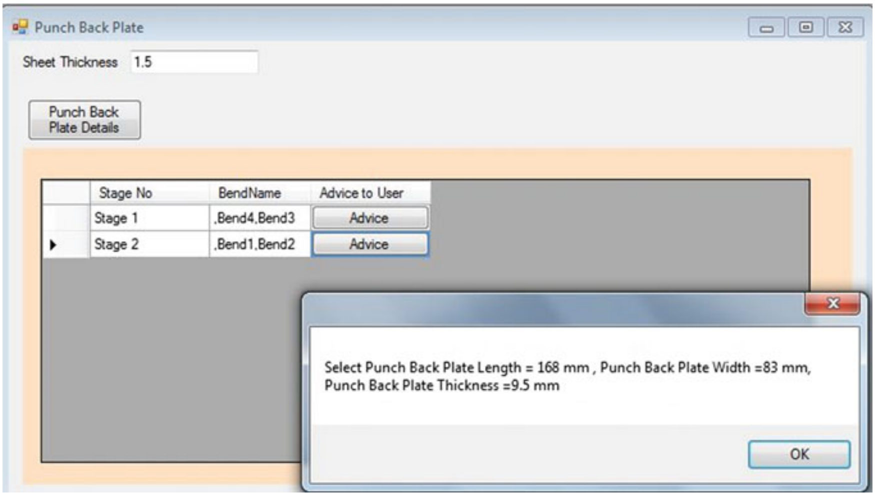


Fig. 36 Output of module PPBPLT for back plate (stage 2)

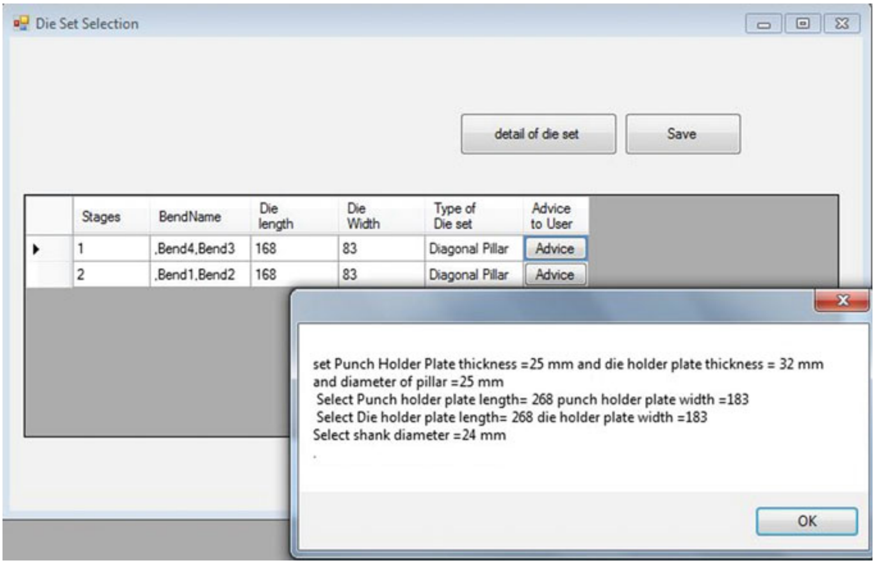


Fig. 37 Output of module DSET for die-set (stage 1)

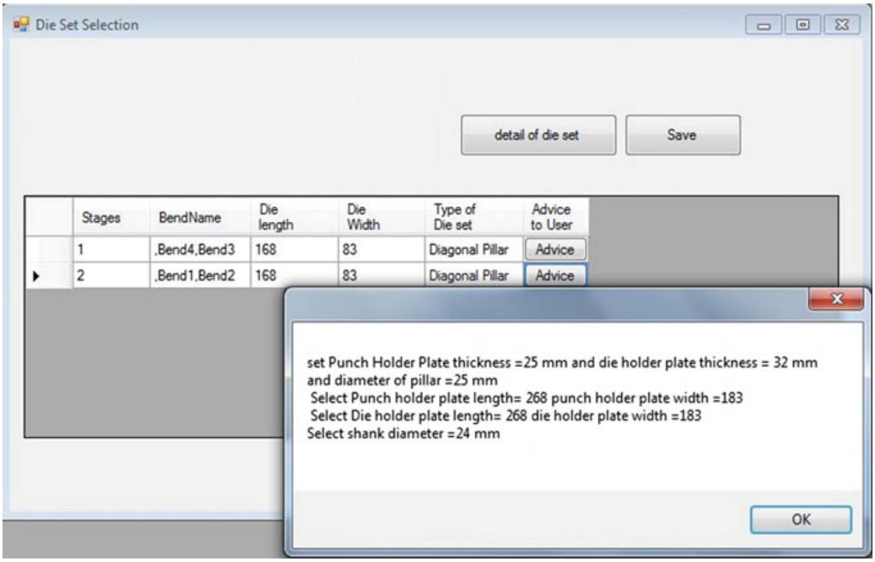


Fig. 38 Output of module DSET for die-set (stage 2)

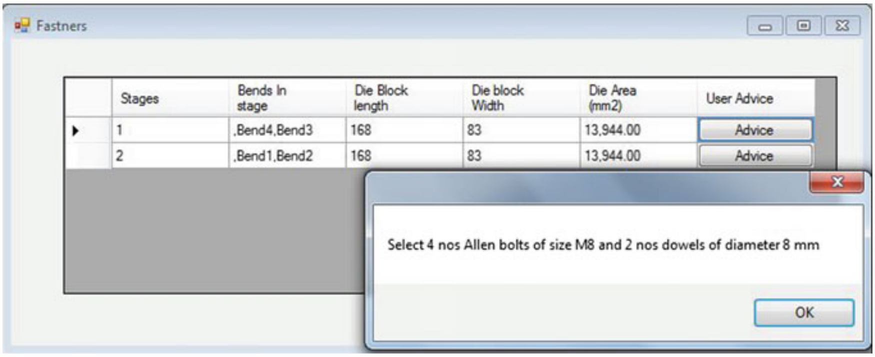


Fig. 39 Output of module FASTNR for fasteners (stage 1)

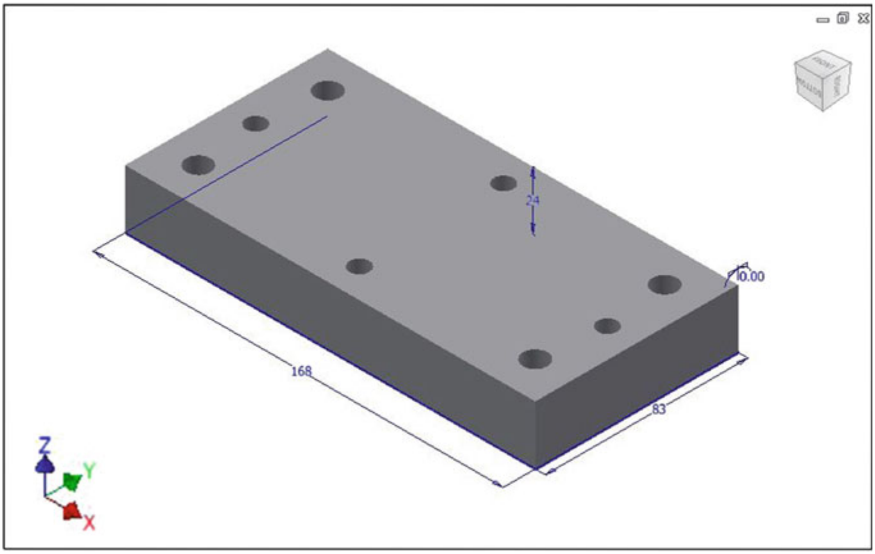


Fig. 40 Output of module DBMOD—3-D drawing of die block (stage 1)

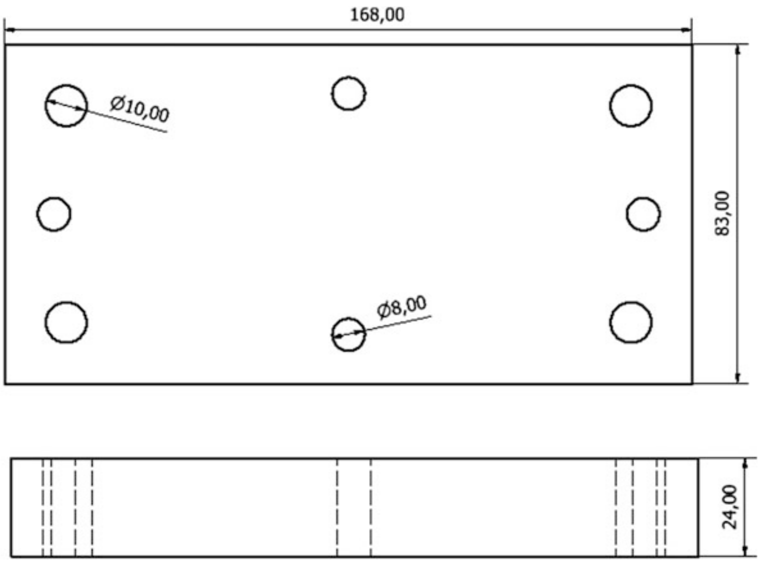


Fig. 41 Output of module DBMOD—2-D drawing of die block (stage 1)

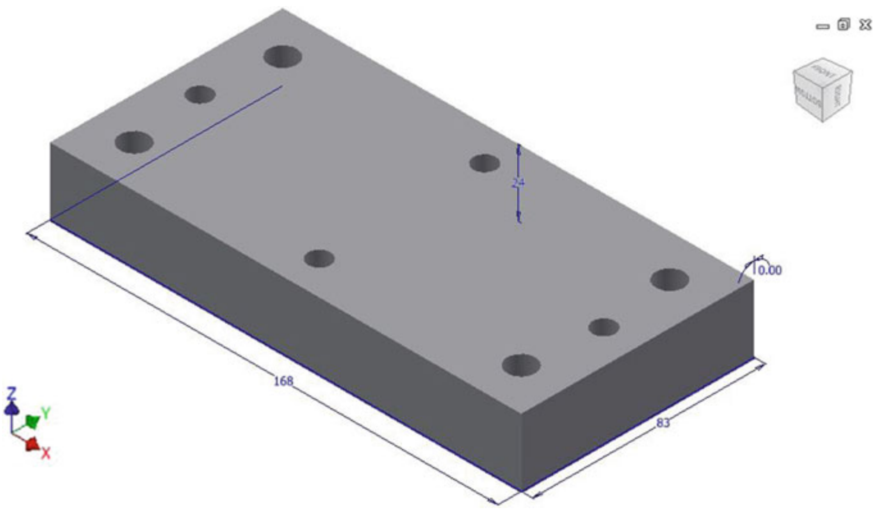


Fig. 42 Output of module DBMOD—3-D drawing of die block (stage 2)

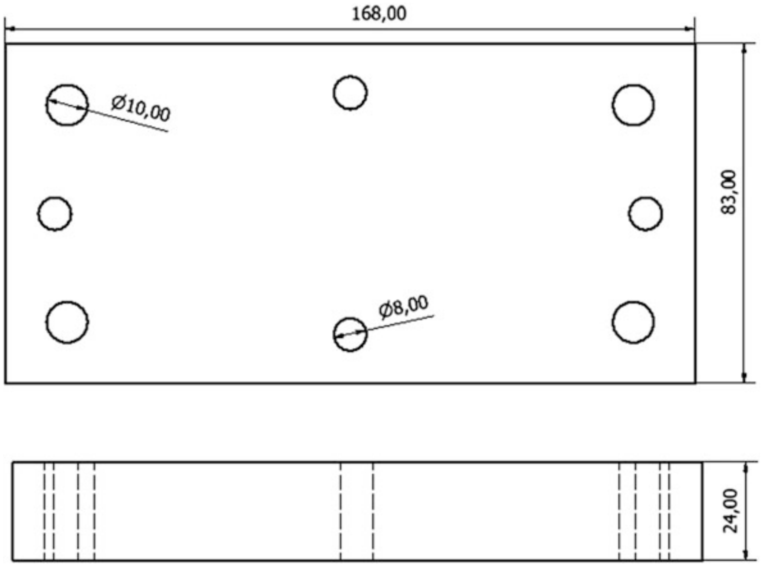


Fig. 43 Output of module DBMOD—2-D drawing of die block (stage 2)

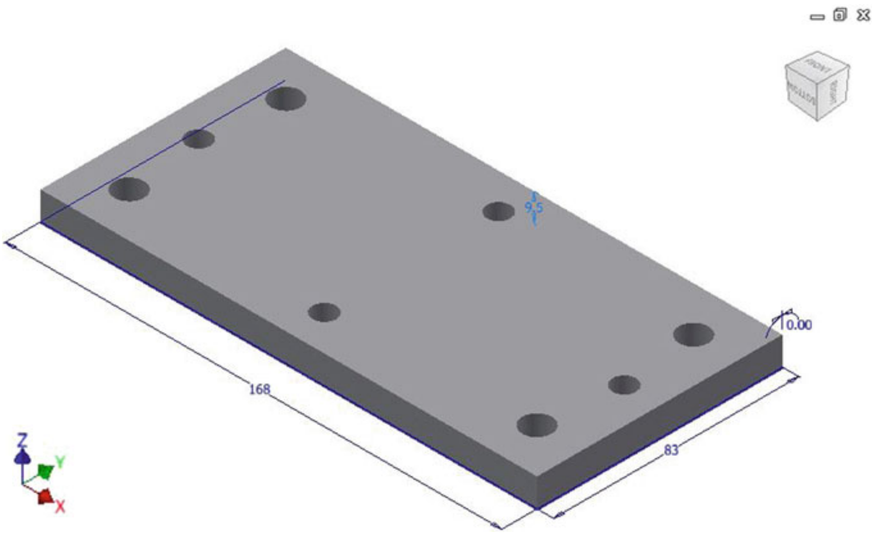


Fig. 44 Output of module DBMOD—3-D drawing of die block (stage 2)

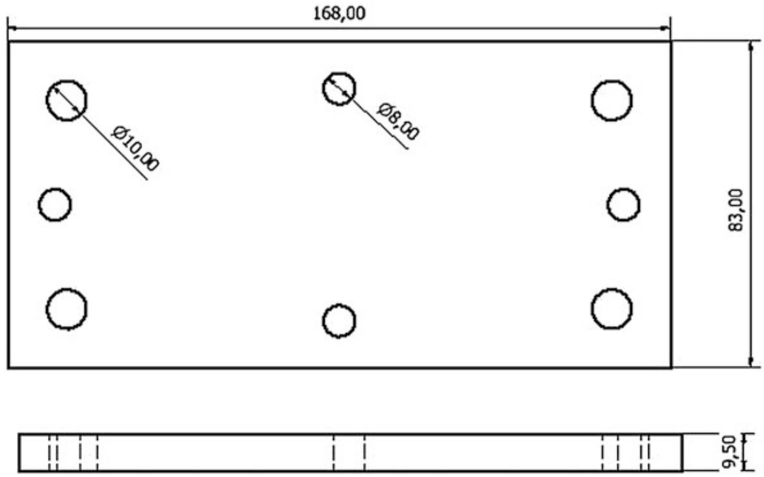


Fig. 45 Output of module DBMOD—2-D drawing of die block (stage 2)

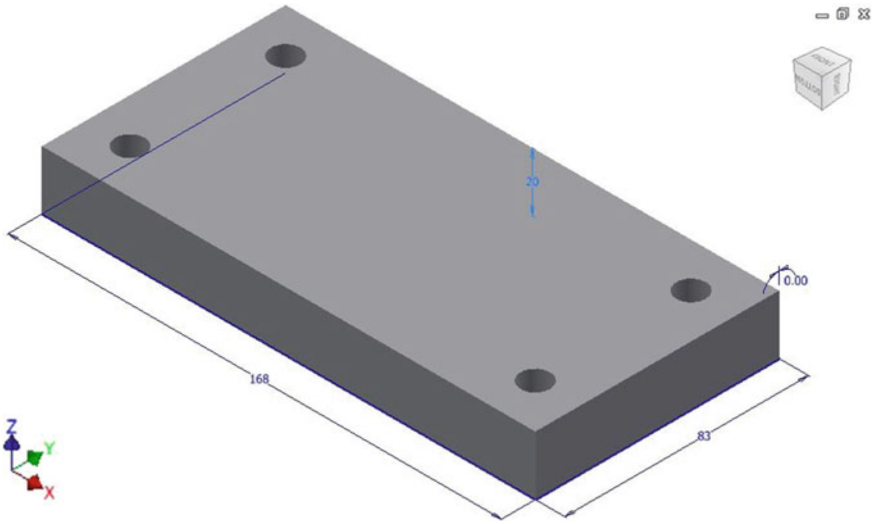


Fig. 46 Output of module STPPMOD—3-D drawing of stripper plate (stage 1)

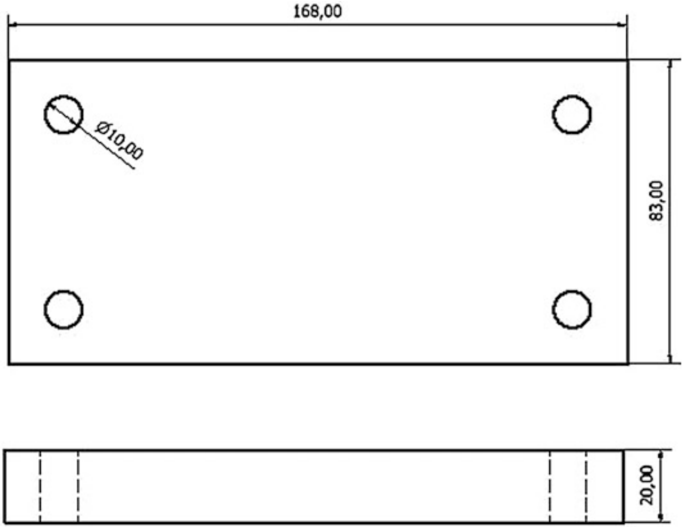
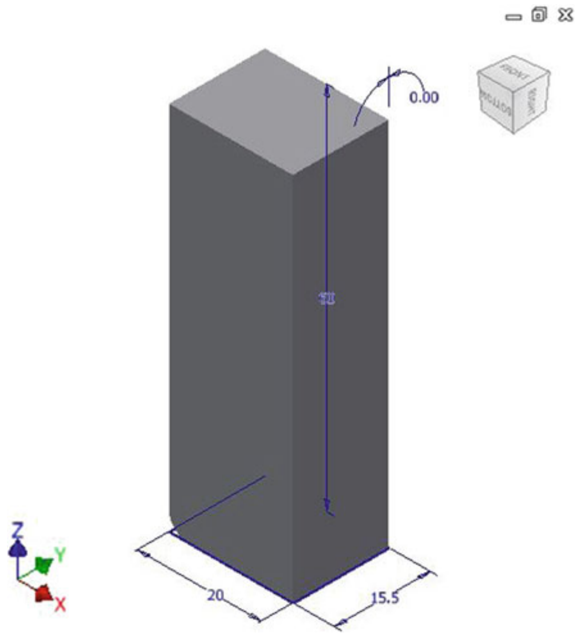


Fig. 47 Output of module STPPMOD—2-D drawing of stripper plate (stage 1)

Fig. 48 Output of module PUNCHMOD—3-D drawing of punch (stage 1)



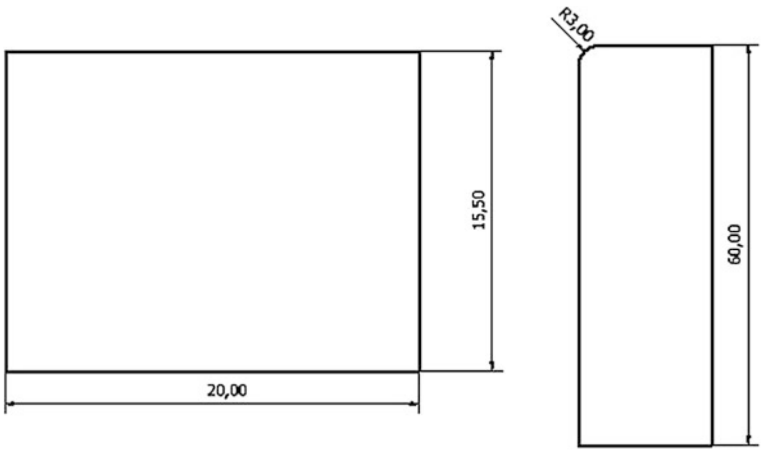
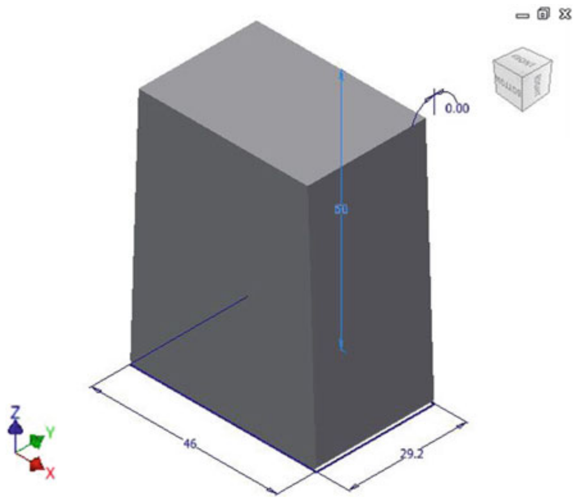


Fig. 49 Output of module PUNCHMOD—2-D drawing of punch (stage 1)

Fig. 50 Output of module PUNCHMOD—3-D drawing of punch (stage 2)



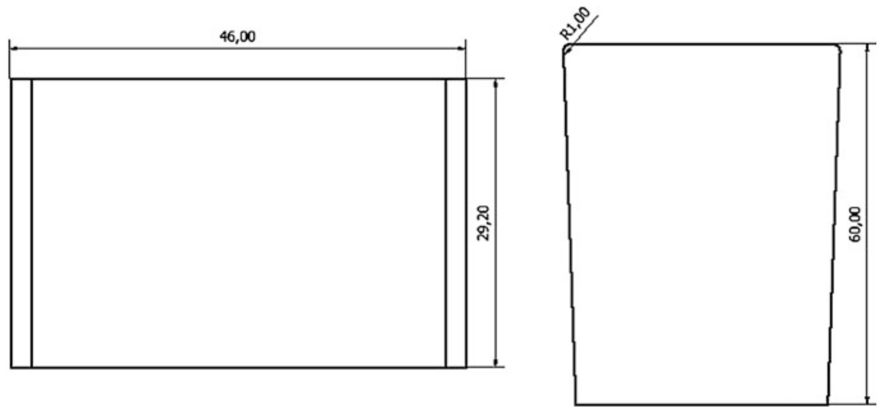


Fig. 51 Output of module PUNCHMOD—2-D drawing of punch (stage 2)

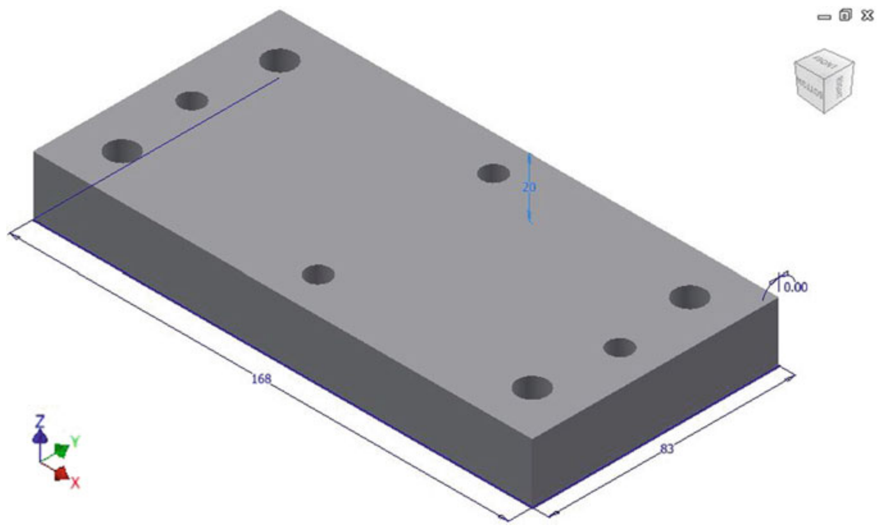


Fig. 52 Output of module PPMOD—3-D drawing of punch plate (stage 1)

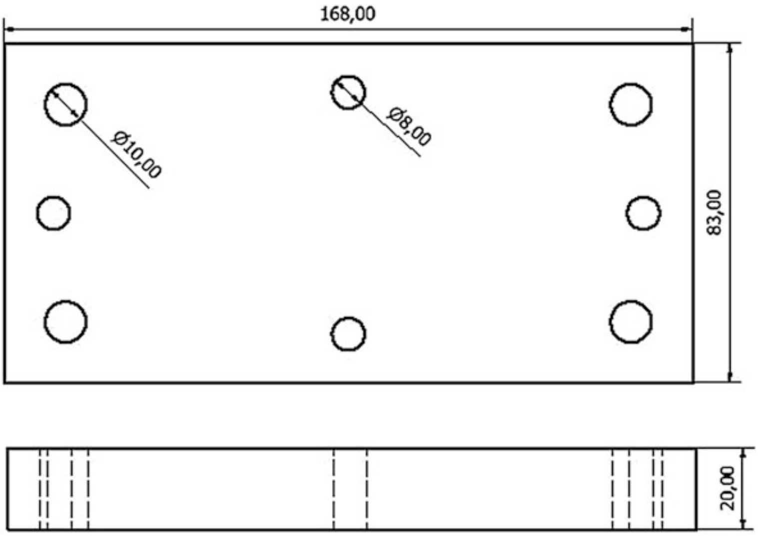


Fig. 53 Output of module PPMOD—2-D drawing of punch plate (stage 1)

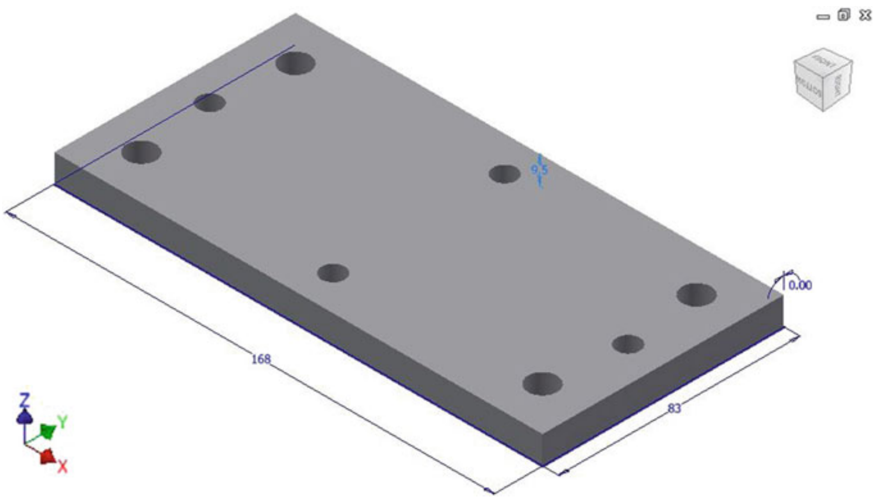


Fig. 54 Output of module BPMOD—3-D drawing of back plate (stage 1)

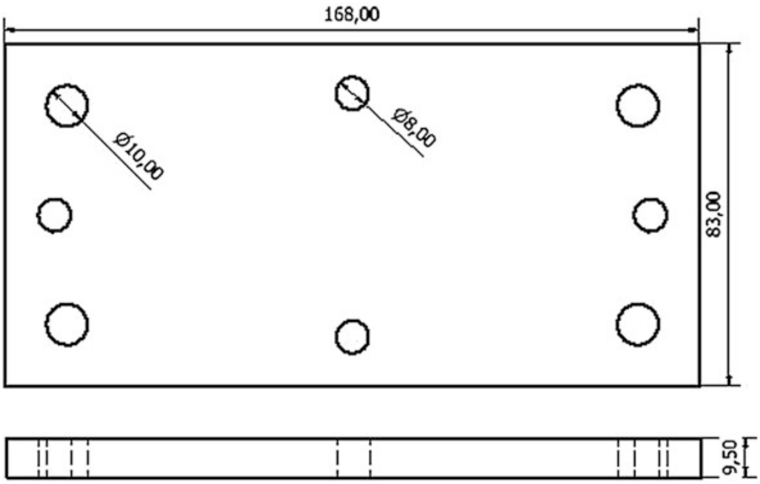


Fig. 55 Output of module BPMOD—2-D drawing of back plate (stage 1)

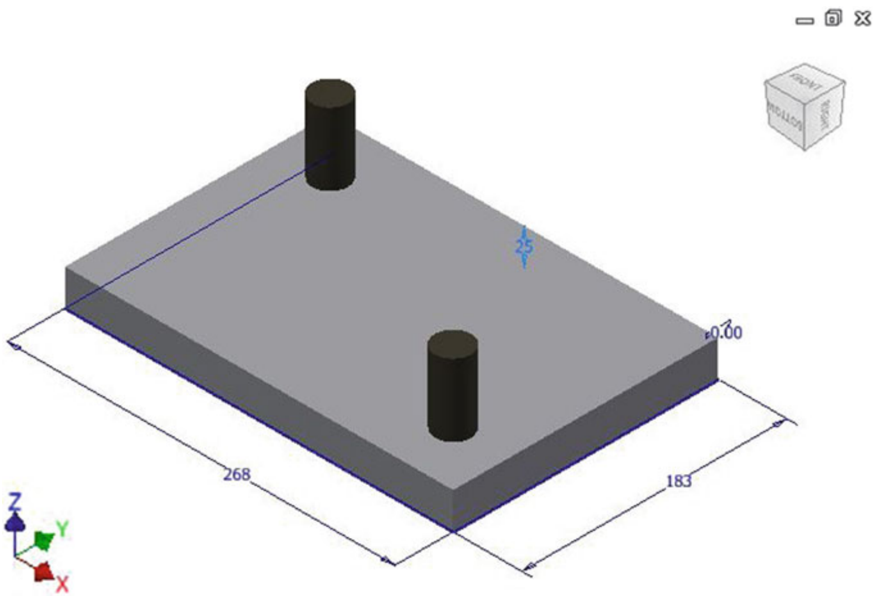


Fig. 56 Output of module DSETMOD—3-D drawing of punch holder plate (stage 1)

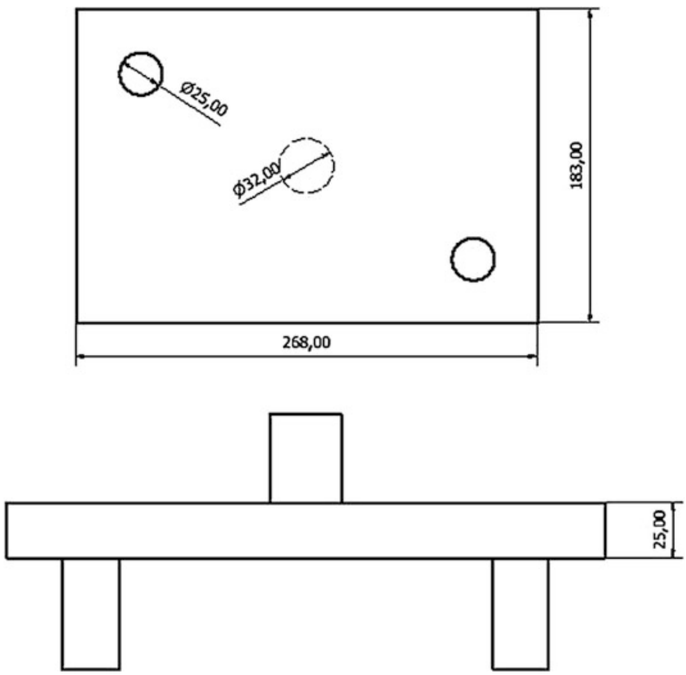


Fig. 57 Output of module DSETMOD—2-D drawing of punch holder plate (stage 1)

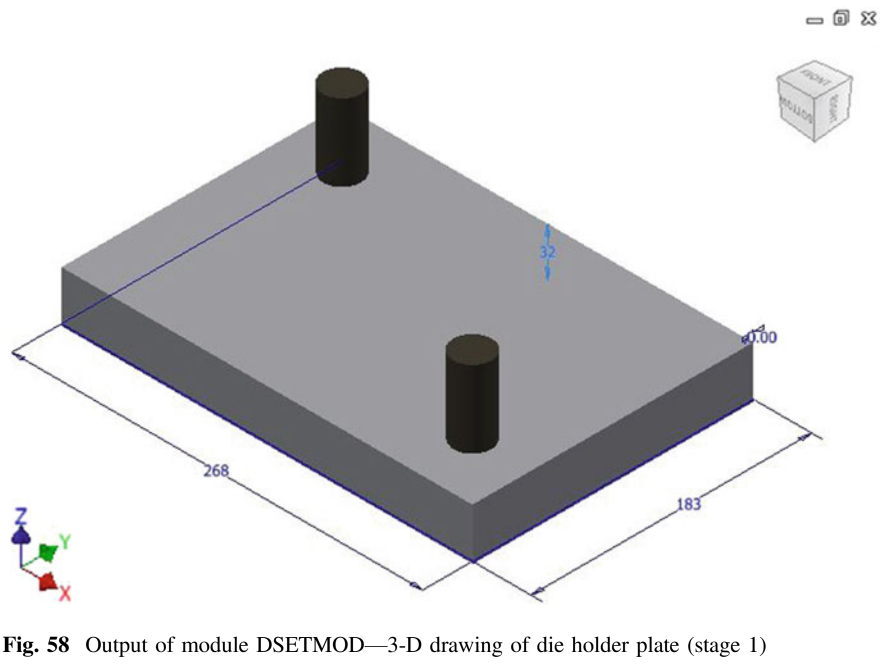


Fig. 58 Output of module DSETMOD—3-D drawing of die holder plate (stage 1)

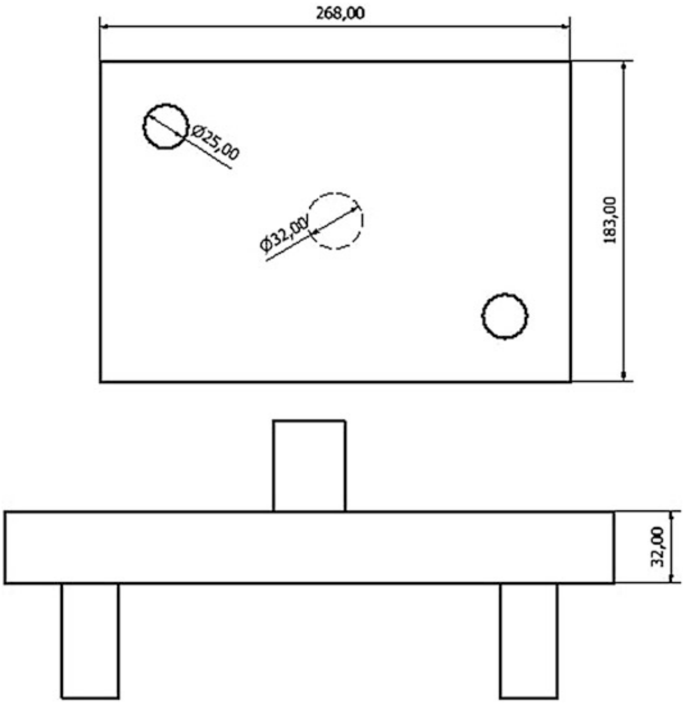


Fig. 59 Output of module DSETMOD—2-D drawing of die holder plate (stage 1)

5 Conclusions

The developed system automates all major activities of design of bending dies including process planning, selection of type and size of die components, and modeling of die components and die assembly. The system takes most of the required inputs directly from the output data files generated during execution of CAD system of automatic feature extraction and KBS of manufacturability assessment as discussed in Chap. 3. Thereafter, the system modules select various process parameters like bend allowance, part blank size, bend sequencing, and bend force. Next, the system selects the type and size of various die components including die block, stripper plate/pressure plate, punch(es), punch plate, back plate, die-set, and fasteners. Finally, the system generates 2-D and 3-D drawings of all major die components, and bottom and top die assembly of bending die. These drawings can be directly used for die manufacturing. The developed system has been tested successfully on various types of sheet metal parts taken from stamping industries. The system is integrated and parametric in nature.

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