Int J Adv Manuf Technol (2000) 16:370–375

The International Journal of Advanced Manufacturing Technology

A Hybrid Intelligent Systems Approach for Die Design in Sheet Metal Forming

R. Pilani[1], K. Narasimhan[1], S. K. Maiti[2], U. P. Singh[3] and P. P. Date[2]

[1]Department of Metallurgical Engineering and Materials Science, IIT Bombay, India; [2]Department of Mechanical Engineering, IIT Bombay, India; and [3]School of Electrical and Mechanical Engineering, University of Ulster, NI, UK

Die design is heavily experience based and the die design process is an iterative procedure of trial and error in order to obtain a final die design for the successful manufacture of stampings. Most automotive industries use internal guidelines and past experience for die design. Even though powerful computer-aided design systems are being used in automotive industry, the lack of adequate analysis tools at the initial die geometry design stage hinders the die manufacturing process, and also necessitates lead times of the order of 5–30 weeks [1]. At the concept design stage, and during the initial die development process, the variations in geometry and process conditions are so large that it is prohibitively expensive to use 3D finite element analysis. The complexity of die design heuristic knowledge hinders the development and application of knowledge-based systems.

Hybrid intelligent systems are computer programs in which at least one of the constituent models simulates intelligent behaviour [2]. These models could be knowledge-based systems, artificial neural networks, fuzzy logic systems, etc. In this approach both artificial neural networks, knowledge-based systems and finite-element analysis (FEA) for modelling the design process are used. A simulation-based design approach [3] for the die design process is followed. Artificial neural networks (ANNs) are preliminary design tools which indicate the formability of the component geometry, for the selected process and material conditions. The ANN module is trained from FEA results for a generic set of component geometries, process conditions, and material properties. The final die design validation is carried out by FEA. The intelligent framework incorporates rules for material selection, process parameter selection and their modification.

Component geometry is a critical parameter which affects the manufacturability of the given part. Hence, an intelligent geometry handling module, which automatically modifies and optimises the geometry of the designed die, is implemented in the present system.

Knowledge-based blackboard architecture is used for the integration of various analysis models such as CAD, FEA, and ANN, as an intelligent framework for die design [4]. The hybrid intelligent system provides an integrated decision support environment for simulation and analysis of the forming process, both during the initial die design phase and during the die tryout phase. The hybrid intelligent systems approach supports the capability for automatic evaluation of prospective die design for manufacturability, and performs automatic modification of design inputs. Applications of the hybrid intelligent system for die design are described together with a comparison with shop floor data.

Keywords: Die design optimisation; Hybrid intelligent system

1. Introduction

In the automotive industry, dies are used to transform a sheet metal blank into a sheet metal component having complex geometry with well-defined shape, size, appearance and properties. The desired component geometry is stored in the dies and imparted to the material with pressure through a die–material interface [5]. Design of dies is a complex procedure and, typically, die design takes 20% of the lead time from concept design to the final stamping manufacture [1]. It is estimated that decisions made at the product design stage determine 70%–80% of the manufacturing productivity [6]. Hence, determination of initial die geometry is an important phase of die design, as it influences the final product manufacturability and appearance. The shape of the die face geometry for automotive panel surfaces is of critical importance in stamping design. Non-homogeneous die face geometry results in imperfect highlight lines, dimensional inaccuracies, and failures such as tearing, splitting, and wrinkling. In conventional die design practice, a process of trial and error is used, resulting in considerable lead times in the production of the stamping dies. CAD/CAM systems offer die-designers productivity increase through reduction in drafting, visualisation, and accurate storage, and retrieval of component geometric data. However,

Correspondence and offprint requests to: Dr U. P. Singh, The Advanced Forming Group, University of Ulster, Newtonabbey, County Antrim, BT37 0QB, UK. E-mail: up.singh@ulst.ac.uk

CAD/CAM outputs are based on die designers' experience for die face design. Hence, for new component geometries and innovative materials, the die design process becomes a highly complex and time consuming task. Application of finite-element analysis (FEA) for assessing formability during the initial die face design phase is prohibitively expensive [7]. FEA requires considerable expertise in setting up the initial model, meshing the geometry, applying the material and processing boundary conditions, executing the FEA model, and analysing the outputs. In addition, FEA provides forming simulation for full component geometry, which is not required at the initial phase of die design.

Knowledge base systems (KBSs) are intelligent computer programs which simulate human decision-making ability though the use of a separate reasoning engine and a set of design rules stored in the knowledge base. Since the die design is highly experience based and depends upon designers' past experience and company guidelines, very few KBSs have been developed in the sheet metal forming arena and they are usually limited to prototype models [5,8–10]. Development and application of KBSs for die design is highly complex and these knowledge bases are brittle. Additionally, the knowledge acquisition process for gathering design knowledge from human experts is a major bottleneck in the development of knowledge-based systems. Traditional die design practice consists of the various stages starting from product conceptual design to initial die face design, die manufacturing and die tryout. During this cycle of design, manufacture, and verify, human experts generalise from past experience, perform modifications to obtain defect-free design, and learn. Current CAD/CAM/FEA tools lack this important self-learning characteristic.

In this work, a hybrid intelligent system for design is developed to aid the engineer during the die design process. Figure 1 presents the various modules and the design methodology used by the hybrid intelligent system. The system incorporates FEA modules and artificial neural network (ANN) modules in an intelligent knowledge-based system framework. The ANN module is a preliminary design tool which indicates formability of the component geometry, for the selected process and material conditions. The ANN module is trained from FEA results for a generic set of component geometries, process conditions, and material properties. ANNs are computational structures modelled on the basis of biological neural networks. The potential benefits of ANNs extend beyond the high computation speeds provided by massive parallelism. ANNs are robust, fault tolerant, and have the ability to adapt and continue learning. An ANN works in parallel with the design process in an off-line mode (training phase). The fully trained network is then invoked when needed for the actual design process. This mode of off-line training of the network and using the trained network for the actual design reduces the number of FEA-based design iterations required, leading to considerable savings in time and cost. FEA is used for final validation of the design. The intelligent knowledge based framework supports integrated simulation and analysis. The blackboard architecture is used for the development of the intelligent knowledge-based framework [11].

The hybrid intelligent systems approach for design incorporates rules for the selection of various design parameters such as process parameter values for lubrication, sheet thickness, punch velocity, and blankholder pressure. Automatic selection of the design parameters is based on heuristic rules in a design knowledge base. During the stamping process, defects such as splitting, tearing, and wrinkling are encountered. Human experts apply their past experience to diagnose these defects and rectify them. Similarly, in the present hybrid intelligent systems approach, heuristic rules for defect diagnosis and rectification are stored. Similarly, selection of material properties is made from the material knowledge base.

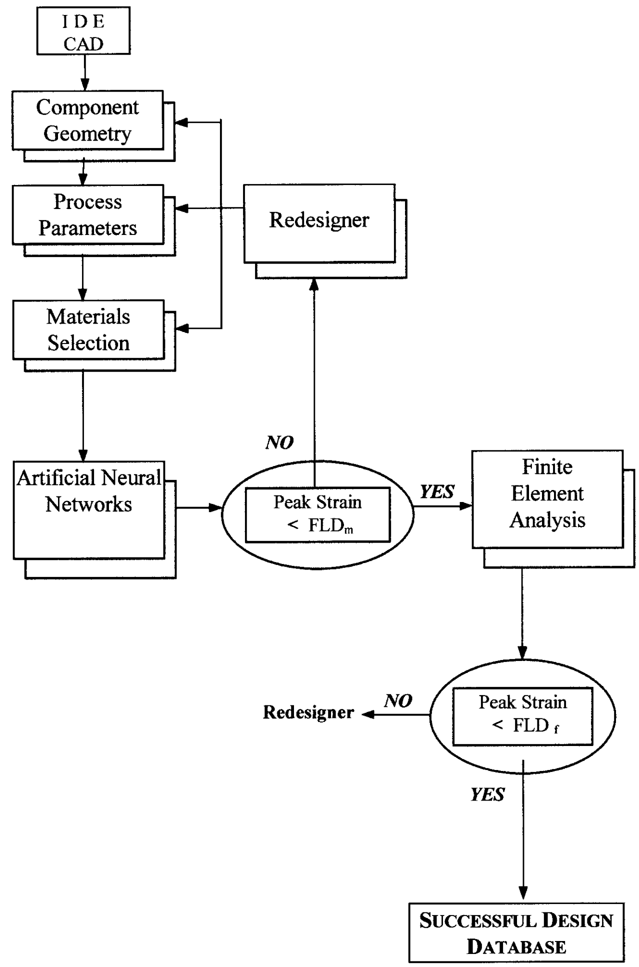

Fig. 1. A hybrid intelligent system for die design.

The geometric optimisation module assists in the detection and automatic rectification of forming defects such as splitting failures. Case studies illustrating this procedure are included. A comparison of the hybrid intelligent systems approach for die design optimisation with shop floor data is also discussed in this paper.

The hybrid intelligent systems approach demonstrates the capability of evaluation of die designs for manufacturability and performs automatic modification of various design parameters to obtain a defect-free design. Application of the hybrid intelligent systems approach, reduces the total lead time for stamping die design and manufacturing.

2. Die Tryouts

During the die tryouts the formability of the component is assessed by stamping trial components to investigate the sheet material, process parameters, and die geometry combination. If any forming defects are detected, then, based on past experience, the experts modify the initial design conditions, such as lubrication, drawbead shape, size, location, blankholder pressure, etc. to enable the component to be formed successfully. Common forming defects are splitting failures, tearing, wrinkling, etc. The die tryout process consists of the initial selection of various design parameters, forming the component, checking the formed component, defect diagnosis, and then rectification, to eliminate any failures that might have occurred.

Currently, for 80% of the time when forming defects are detected, the experts rely on heuristic knowledge gained over the years for die modification and design optimisation to avoid the failures. Only in about 10% cases, do they seek the assistance of FEA tools and design handbooks to rectify forming defects [1].

In the automotive industry, CAD/CAM and FEA tools provide separate support for geometrical design and analysis, but do not provide integrated design and simulation support, including automatic set-up, execution and analysis. Additionally, the need for heuristic knowledge during the die design process is not considered in these systems. Lack of user friendliness and the complicated set-up and analysis of FEA systems are some of the reasons for the lack of widespread applications of FEA [1].

3. Hybrid Intelligent System

3.1 Objectives

Since the die design process is an iterative trial and error process, and the design knowledge and data are so complex, there is a critical need for integrated systems which combine various problem-solving technologies such as FEA, ANN, and KBS in an integrated design framework. Such a system needs to possess an intelligent reasoning mechanism for automatic selection of the appropriate problem-solving technology, and the ability to schedule and process the results from the problem solver, to achieve the desired design goals.

Hybrid intelligent systems are problem-solving systems that are based on the integration of several technologies where at least one is an intelligent technology [2]. Hybrid systems are available in areas such as architectural design [12], turbine design [13], and aluminium alloy design [14]. These hybrid knowledge-based systems integrate expert systems with numerical methods and computer-aided design. These techniques provide the accuracy needed for solving complex problems as well as the reasoning needed for arriving at a solution quickly. The development of such systems for sheet metal forming is difficult since the die design process is very complicated, and the Human experts use various kinds of information at different times during the design process. The information could be either numerical or symbolic. Hence, a hybrid intelligent system that supports both symbolic and numerical processing technology is required.

With the above requirements in mind, a hybrid intelligent system for die design with the following objectives has been developed:

1. Integrated design and simulation.
2. Intelligent set-up and automatic modification of design parameters.
3. User friendly.
4. Self-learning and generalising capability.

By the integration of design and simulation, the expensive and laborious task of fine-tuning the analysis model is reduced. Additionally, the effect of changing one design parameter may affect other parameters which requires accurate bookkeeping of cause and effect which are taken care of in the hybrid system. The incorporation of an ANN model provides a self-learning and generalisation capability.

The application of intelligent tools to incorporate human design expertise enhances the performance of analytical tools by the automatic selection of appropriate factors for the following design parameters:

Analysis model: ANN or FEA.

Material model: voce or holloman hardening laws.

Sheet material: DQ, EDDQ, DDQ, IF, CQ, etc.

Lubrication: high, low, or medium.

Forming mode: draw, stretch or mixed mode of forming.

3.2 System Architecture

The hybrid intelligent system developed in this work, intelligent design environment (IDE) is based on an artificial intelligence blackboard architecture. Blackboard systems are conceptual frameworks for integrating multiple independent programs, having diversity in knowledge representations and opportunistic problem solving [11]. IDE incorporates groups of independent modules consisting of ANN programs, FEA programs, and KBS. The intercommunication between the programs is through the common blackboard. An intelligent scheduler reviews the blackboard after each call to the knowledge source. Based on the success or the failure of the called and executed knowledge source, the scheduler decides the agenda and plans the design process dynamically. IDE incorporates various modules such as defect diagnosis module, geometry modification module, etc. which are discussed in detail elsewhere [15,16].

The design methodology is shown in Fig. 1. Initially the user develops the component geometry through IDE CAD, after which the various process parameters such as lubrication, punch velocity, etc. are selected. Suitable material for forming is also selected by the hybrid intelligent system. The ANN module is then invoked which predicts the peak strain value for the given geometry. If the peak strain value exceeds the forming limit value for the selected material, then the redesigner module optimises various design parameters such as lubrication or blankholder pressure to arrive at a design which exhibits lower peak strain. In the next phase, the FEA module is invoked which predicts strain distribution over the whole component geometry. If forming defects such as splitting are detected then, by optimisation of the process, and material or/and geometry parameters, the defect is eliminated. The user can override the modifications suggested by the system.

3.3 Knowledge Bases

The knowledge bases of the present hybrid system are similar to the knowledge base developed in [13]. There are four main knowledge bases:

Scheduler KB
Parameter KB
Analysis KB
Optimisation KB

Scheduler knowledge base. This knowledge base consists of rules for managing the selection of suitable knowledge sources, the selection of suitable design plans and the execution of the plan. The plan specifies the sequence in which the knowledge sources are to be executed.

Parameter knowledge base. The ANN and FEA programs and their input are determined through this module. The parameters include material properties: *n*, *m* , *r*, *K*, etc. and process parameters such as friction coefficient , punch velocity, blank-holder pressure. IDE attaches current values, minimum increment, default values, etc. to the various parameters. The material parameters are selected from the stored material database.

Analysis knowledge base. This knowledge base contains rules for the extraction of useful information from the output of the various ANN/FEA analysis modules. This includes checking for various forming defects from the data. At present, only splitting failures are analysed.

Optimisation knowledge base. Heuristic rules for modification and optimisation of the various design parameters to prevent failures are stored in this knowledge base.

Geometry modification. During die tryouts, experts frequently modify the die face geometry by polishing, spotting, and smoothing the sharp corners. In the hybrid system, the component geometry is translated into a B-spline representation form. B-spline representation is the most compact and commonly used geometrical representation format in current CAD/CAM/CAE systems.

4. Hybrid Intelligent System: Applications

Two case studies describing the application of the hybrid design approach for an industrial automotive component are given in the following sections. The first case study illustrates the full range of automatic modifications performed by the hybrid design system for a hypothetical component in which

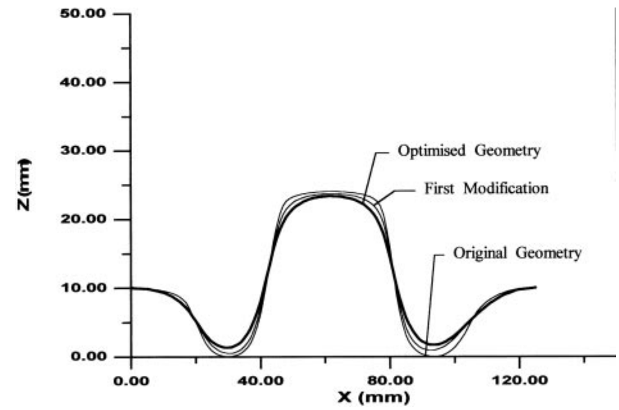

Fig. 2. Tool geometries: original, modified and optimised.

the initial conditions are very severe, and in which splitting failure is detected. By performing automatic modifications in process, for material and geometrical parameters, the hybrid system was able to obtain a defect-free die design. The second case study illustrates the application of the hybrid design system for the die design of an automotive panel section. To model shop floor conditions, only process parameters and geometrical modifications were permitted.

5. Intelligent Die Design Optimisation

The objective of this hypothetical case study is to show how design optimisation as performed by human experts is simulated by IDE. The optimisation is related to the decrease in the peak strain values for a stretch formed component. The optimisation parameters are material, processing conditions, and component geometry. Traditionally, such design iterations and optimisation are performed at the die tryout stage, where the die design is optimised to prevent any forming defects such as tearing or splitting, occurring during manufacturing.

The initial geometry of the component is shown in Fig. 2. The material selected is commercial quality steel having poor formability characteristics with a limit strain of about 0.20%. Process parameters such as lubrication coefficients are also chosen in such a way that severe forming conditions are induced. Figure 3 shows the strain distribution for this compo-

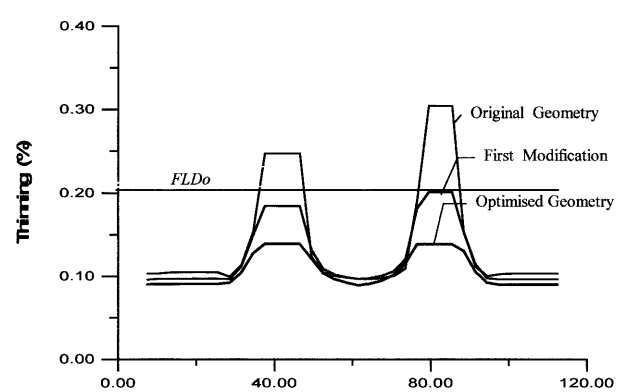

Fig. 3. Strain distribution: original, modified and optimised.

nent. The peak strain values exceeds 0.30, which is above the forming limits for this material.

As the peak strain exceeds the forming limit for this material, the scheduler KS executes the KS for design modification asserting tearing failure at specific locations on the component. The design modification KS calls design rules for design parameter modification relating to material and process parameters.

After the change in lubrication condition and material properties, the peak strain value falls to 0.25 which is still higher than the forming limit for this material. Note these design modification rules are user modifiable and can be customised for individual sites. In the next iteration the tool geometry is modified within user specified limits, which is comparable to the polishing of the sharp edges and corners of the die. This rule is activated since there are no further modifications possible for process or material conditions.

The modified geometry and resulting strain distribution is shown in Figs 2 and 3, respectively. Now, the peak strain is below 20%, which is still in the marginal zone. The user can go through one more round of design iteration for still further reduction in peak strain values. After this design modification, the peak strain value falls to 18% which is in the safe zone (Table 1). An added advantage of the last design iteration, is that during production, even if there is deterioration in process and material conditions, the safety margin makes the forming process more robust.

6. Design Optimisation of an Automotive Component

IDE was tested using shop floor data. For this case study, an existing automotive inner panel section was selected, which satisfies plane–strain conditions approximately [17]. The original tooling was as designed, the tool shape is shown in Fig. 4. This component, however, was found to fail by splitting at the critical section. By trial and error, die design experts modified the geometry to prevent failure in this component. In the section below, the use of IDE for optimising the above automotive inner panel is demonstrated. This component was selected to illustrate the IDE capabilities in modelling the die design process as carried out on the shop floor. Table 2 illustrates the reduction in peak strain achieved using IDE and the corresponding peak strain values from the shop floor measurement.

The original and optimised component geometry is shown in Fig. 4. The material used is a deep drawing quality (DDQ) steel of 0.64 mm thickness. The peak strain obtained was well above the limit strain of 23% for this material (Fig. 5). By using current design variable settings, splitting failure would have taken place. Hence, the scheduler opted for modifications in the geometry. Figure 5 shows the geometry after complete optimisation, at which stage the strain level attained was within the forming limits for the material.

This case study shows the ability of the hybrid systems to suggest and make modifications automatically to critical design variables such as process, material, and geometrical parameters.

Table 1. Design variables and the predicted peak strain values.

Trial	Design variables modified	Peak strain
Original geometry		0.30
Change process conditions	Increase lubrication	0.25
Geometry optimise 1	Geometry at critical section	0.18
Optimised geometry	Geometry at critical section	0.14

Table 2. Design variables and the predicted peak strain values.

Trial	Design variables modified	Peak strain
Original geometry		0.38
Optimised geometry	Geometry at critical section	0.13
Shop floor data	Polishing and smoothing	0.14

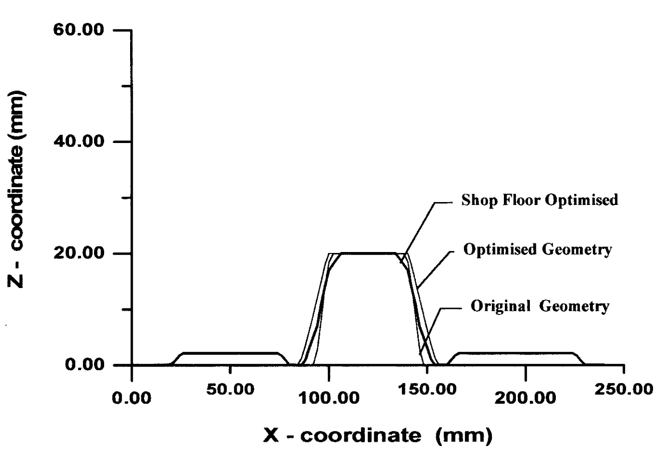

Fig. 4. Die geometries: original, optimised tooling and shop floor final data.

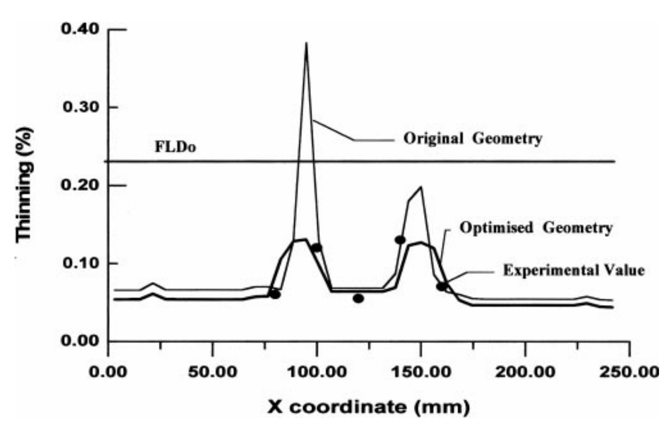

Fig. 5. Strain distribution: original, optimised and shop floor final data.

7. IDE Implementation

The current version of the hybrid intelligent system, known as Intelligent Design Environment is v1.5.1. IDE was developed using Prolog, C/C++ and FORTRAN and runs on a DOS platform. The blackboard system is implemented in Prolog. IDE consists of around 5500 lines of Prolog code, 2500 lines of C/C++ code and the FEA code is in FORTRAN. The knowledge base consists of about 150 rules.

8. Summary

A hybrid intelligent systems approach for die design for sheet metal manufacturing has been developed. Using powerful artificial intelligence techniques, the hybrid system integrates KBS, FEA and ANN. The hybrid intelligent system consists of various modules as knowledge sources, and a scheduler linked through blackboard architecture. The knowledge sources are the individual expert systems, the FEA programs, ANN and the graphics handlers. The hybrid approach has the following capabilities:

1. Hybrid intelligent system integrating finite element analysis, artificial neural networks, and knowledge based systems.
2. Supports conceptual design, and rapid prototyping
3. Automatic evaluation of new designs quickly and accurately.
4. 1. Auto modification and optimisation of geometry.
5. Auto process optimisation for the given component.
6. Self learning capability.

The hybrid intelligent system improves the design quality and reduces the set-up time. The hybrid system is shown to perform automatic setting up and modification of the input process, material and geometry, for evaluating manufacturability. It is shown by the case studies that the hybrid systems approach optimises design by modifying automatically the punch velocity, drawbead force and geometry, blankholder pressure and position, blank size, thickness, material properties, and friction, to eliminate the forming defect.

Acknowledgement

The research project is supported by UK-India Scientific Technical Research Funding.

References

1. P. Fallbohmer, T. Altan, H.-K. Tonshoff and T. Nakagawa. “Survey of the die and mold manufacturing industry”, Journal of Material Processing Technology 59, pp. 158–168, 1996.
2. G. R. Madey, J. Weinroth and V. Shah, “Hybrid Intelligent Systems: ‘Tools for decision making in intelligent manufacturing’”, in Cihan H. Dagli (ed.) Artificial Neural Networks for Intelligent Manufacturing, Chapman and Hall, London, p. 72, 1994.
3. K. F. Reinschmidt and G. A. Finn, “Smarter computer aided design”, IEEE Expert, 23, p. 50, 1994.
4. D. Stacey, “Intelligent systems architecture: design techniques”, in Artificial Neural Networks for Intelligent Manufacturing, Chapman and Hall, London, p. 229, 1995.
5. T. Altan, “Design and manufacturing of dies and molds”, Annals CIRP, 36(2), p. 455, 1987.
6. A. Makinouchi, “Sheet metal forming simulation in industry”, Journal of Materials Processing Technology 60, p. 19, 1996.
7. Mustafa A. Ahmetoglu, Gary Kinzel, and Taylan Altan, “Computer simulation for tool and process design in sheet forming”, Journal of Materials Processing Technology 49, p. 432, 1994.
8. A. Makinouchi and M. Kaska, “Process simulation in sheet metal forming”, Journal of Materials Processing Technology, 46, p. 303, 1994.
9. M. P. Sklad, “Modelling of part shape and deformation evolution in conventional forming of large sheet metal components”, Proceedings of Numisheet 93, 3rd International Conference of 3D Sheet Metal Forming Process, Isehara, Japan, p. 295, 31 August–2 September 1993.
10. T. Nakagawa, “Recent manufacturing technologies for auto-body panel forming tools”, Journal of Materials Processing Technology, 46, pp. 277–290, 1994.
11. P. H. Nii. “Blackboard systems: The blackboard model of problem solving and the evolution of blackboard architectures”, AI Magazine, pp. 38–53, Summer 1996.
12. D. Sriram, R. Logcher, N. Groleau and J. Cherneff, “DICE: An object oriented programming environment for cooperative engineering design”, Artificial Intelligence in Engineering Design, 3, pp. 230–252, 1992.
13. S. Tong, D. Powell and D. Cornett, “Engineous: A unified method for design automation, optimization and integration”, Artificial Intelligence in Engineering Design, 3, pp. 210–228, 1992.
14. I. A. E. Hulthage, M. S. Fox, M. D. Rychener and M. L. Farinacci. “Alladin: A knowledge based system for aluminium alloy design”. IEEE Expert, pp. 56–73, August 1990.
15. R. Palani, R. H. Wagoner and K. Narasimhan. “Intelligent design environment: A knowledge based simulations approach for sheet metal forming”, Journal of Materials Processing Technology 45, pp. 703–708, 1994.
16. R. Palani and K. Narasimhan, “An integrated approach to design in sheet metal forming”, in T. S. Mruthyunjaya (ed.), Proceedings of Conferences of Advances in Mechanical Engineering (ICAME), Narosa Publishing House, New Delhi, India, pp. 637–650, 1995.
17. Y. T. Keum, C. Wang and R. H. Wagoner. Sheet-S v 2.0: Industrial Trials and User’s Guide, Ohio State University, Ohio, USA, 1990.