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ORIGINAL PAPER

Sheet metal cutting and piercing operations planning and tools configuration by an expert system

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Abstract This paper describes the development of an expert system for both process planning and die design of sheet metal cutting and piercing operations. Knowledge for the system is acquired from practical handbooks, theory and empirical knowledge from industrial partners and is expressed as "crude" rules, transformed by the knowledge engineer into production rules. These are then coded into constructs of the CLIPS expert system development environment. This process is explained using a number of examples. The expert system comprises of five modules: initial calculations (including data input), process planning, finishing operation, die and press selection, and tools selection. Each module draws upon one or more among 18 rule pools defined around the important notions characterising the problem studied. The results of the expert system can be used by both the designer deciding on the production feasibility (manufacturability) for a sheet metal component and by the manufacturer receiving advice either on the hardware needed or on the process plan.

Keywords Sheet metal · Cutting · Piercing · Expert system · CLIPS

1 Introduction

Die design and process planning for sheet metal parts are recognised as being heavily experience-based. Product and die design and production are still practiced as two stand-alone operations, thereby creating the need to bridge them together or carry them out in parallel using intelligent tools.

Among the variety of issues in die design and process planning for sheet metal parts, well-defined particular problems have been treated using largely algorithmic approaches aided by numerical techniques. Examples refer to optimisation of die tool wear in deep drawing using FEM and a semi-empirical wear model [1], problem prediction in die design for multi-step forming using FEM analysis [2] and algorithmic optimisation of stamping die blank layout in a CAD environment [3].

Intelligent approaches have been employed to address usually the full breadth of the problem of planning the process and designing the tools to implement it, rather than focusing on specific problems. Pilani et al. [4] presents a rather comprehensive system for stamping process planning. This involves artificial neural networks trained with FEA results to provide assessment of stamping behaviour and knowledge bases for setting various process parameter values and even geometric reasoning in a blackboard architecture. Disappointingly, besides system architecture, very little useful information is provided on internal details of the system. Li et al. [5] consider sheet metal bending with a feature- and rule-based approach and Choi et al. [6] tackle blanking and piercing of irregular-shapes with a knowledge-based approach, both using product descriptions from a CAD environment. In [7], an expert system for process planning of deep drawing operations is developed using production rules. In [8], a system decides the sequencing process in the presence of intricate piercing and bending operations by applying fuzzy set theory on bending factors and using expert rules. An expert system approach strongly guided by geometry features is presented in [9]. In [10], an expert system was developed running in a

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CAD environment and using 150 production rules. A combination of production rules and frame representation was used in [11] to develop a hybrid expert system for blanking.

In some cases, expert systems were developed for more specific applications, such as progressive die design of electron gun grid parts [12]. In [13], an expert system selects optimal presses using the IF-THEN paradigm.

Three main observations have been made from literature reviewed, forming the incentive of this work. First, all papers reviewed seem to be based on almost elementary knowledge bases consisting of a restricted number of rules, perhaps as proof-of-concept rather than as tools of practical importance. Indeed, the real difficulties in terms of acquiring the knowledge, converting it into computer-readable form and structuring it in order to obtain expert results in reasonable time, emerge with large knowledge bases. Second, no mention is made of the way in which crude knowledge is transformed into expert system knowledge, which is essentially a knowledge elicitation phase influencing system response. Third, it seems that sheet metal cutting and piercing operations have not attracted enough attention as yet.

The expert system described in this paper, addresses all three issues identified and aims at both the designer and the manufacturer. The designer can be informed of problems that might occur later in the production stage and be advised on ways to overcome those problems, while the manufacturer is instructed on the hardware needed to build the die and on the process plan itself. The expert system was developed using CLIPS, which provides a complete environment for the construction of rule and/or object based expert systems.

Section 2 of this paper describes the main modules of the expert system, while Sect. 3 focuses on CLIPS. The development of the expert system and the rules used for this purpose are analysed in Sect. 4. Examples of system use are given in Sect. 5 and conclusions are summarized in Sect. 6.

2 System structure

The expert system comprises of five modules, see Fig. 1: initial calculations (after data input), process planning, finishing operation selection, die and press selection, and tools selection. The system always starts with the “initial calculations” module, which is the prerequisite for all other modules, as described next. The working principle of the system is that of an expert system. The modules cannot be run separately, because knowledge employed in some of them may result from other modules, i.e., there is intrinsic inter-dependence among the domains covered. The system is highly interactive, i.e., the user is in a continuous dialog with the system, his/her answers typically leading to further questions. Between questions, the system processes the answers and, in combination with the in-built knowledge, proceeds to conclusions. Some of them are immediately presented to the user, while intermediate ones are kept to be presented when the reasoning line has to be explained.

Although the system has a specific starting point, there is no specific ending point. Reasoning flow depends completely on the answers given by the user, and the system halts only if there are no more questions to ask, or if it comes to the conclusion that the operation cannot be accomplished.

In the initial calculations module the user enters the initial data necessary for the system, i.e., material type, sheet thickness and dimensions, dimensions of cuts and their positioning on the sheet and material grade or material shear strength directly. The user is then asked to decide on the objective of the process, deciding between surface quality and least cutting force.

The process planning module concerns the cutting phases and the necessity of a finishing operation. Of crucial importance are cutting edge requirements, possibly falling into one of five types. Edge requirements drive the system to different conclusions in each case. The five possible edge types are: edge quality not important, general purpose (large burnish not required), low residual stress, good quality and maximum quality. Additional input required concerns the existence of areas with dense holes and the required production run. The main intermediate results of this module are essentially operation characteristics such as material deformation limit, initial cutting clearance, cutting surface characteristics expected (fracture angle and depth, burnish and rollover depth), the kind of burr expected, and minimum necessary dimensions of cuts (holes distance, single holes and square or rectangular cuts at the sheet edge).

The finishing module is activated when a finishing operation proves necessary in the process planning module. Possible finishing operations are: shaving, reaming and fine edge piercing. In each case, the number of necessary finishing passes is calculated and the clearance recommended in each pass. Critical factors for the finishing operation are: material type, sheet thickness and percentage of cut wall that needs to be uniform. Critical comments are also presented to the user concerning scheduling of the finishing phase in relation to the cutting phase, use of a tool with replaceable inserts for the operation and necessity of sheet locating devices, such as pilot pins.

The die and press module estimates the cutting force based on the length of cuts on the final product, the stripping force to cutting force ratio, which is a crucial criterion for stage punching or sheared punches – with

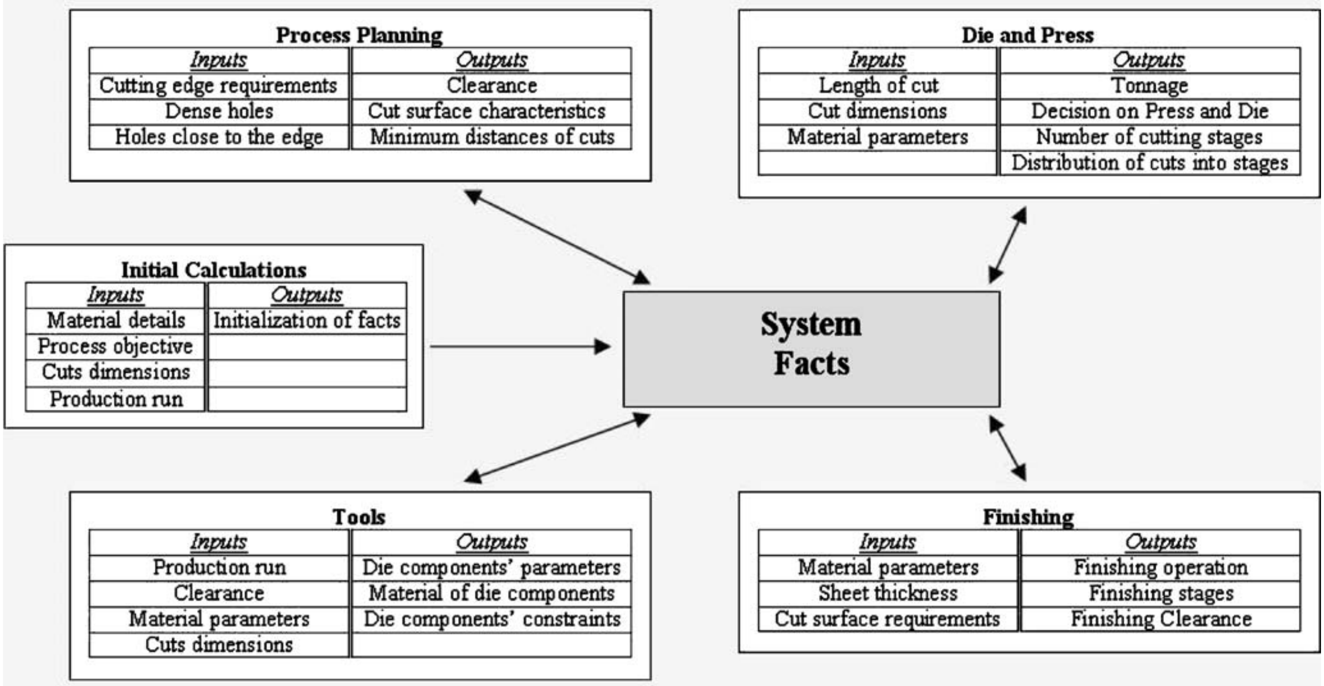


Fig. 1 Expert system knowledge structure. Each module is presented with its main input and output factors

possible force correction– the tonnage of the press and the die to be used for the process, e.g., single operation, progressive or compound die, taking into account not only part geometry but also the production run. Many more pieces of advice are produced on the way, such as the stage at which a progressive die pierces the pilot holes, distribution of cuts among different cutting stages, the scheduling of cuts before and after a possible forming operation.

The tools module is the largest in terms of information processed and produced, focusing on die design or, more precisely, die configuration involving a large variety of components, see Fig. 2. The system can select the appropriate punches for each case (e.g., conventional, standard quill, etc), recommending punch material and hardness, punch diameters, punch length limit, guidance of the punches (heels, multipart retainers or four pillar die sets) and punch bushing (material, type and dimensions). The system also advises on guidepost material and height, their positioning and their type including bushings. Information covers almost all parts of the die, including, among others, the punch plate, the die shoes, the stripper, the knock-out pins and the die openings.

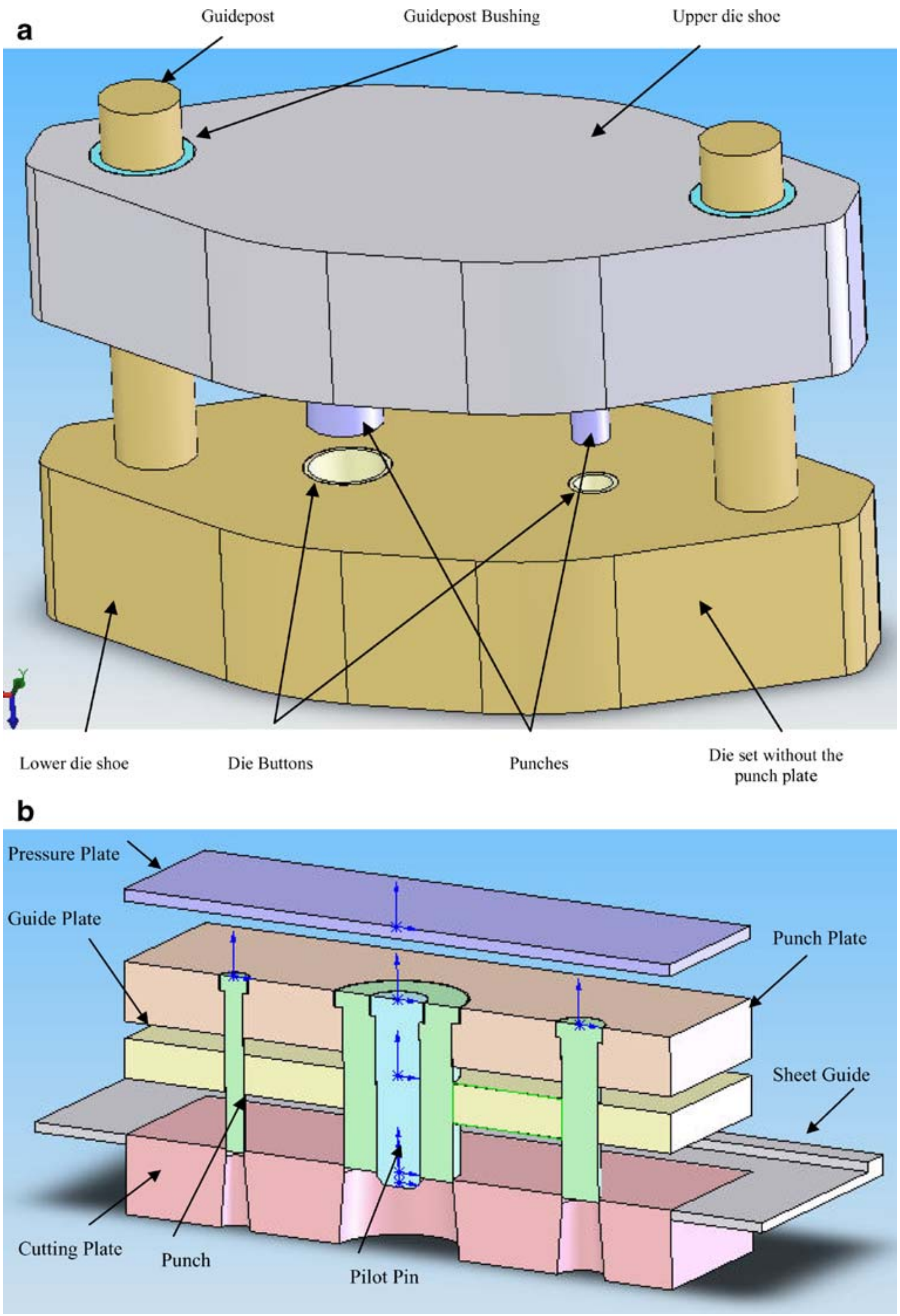
3 CLIPS: the expert system development tool

CLIPS is a productive development and delivery expert system tool which provides a complete environment for the construction of rule and/or object based expert systems. Created in 1985, CLIPS is now widely used throughout government, industry, and academia. It has the following key features [14]: support for three different programming paradigms (rule-based, object-oriented and procedural) portability due to availability of source code in C; integration and extensibility through the use of several well-defined protocols; interactive development support including various text and menu-based interfaces for debugging, help, and editing etc.; verification and validation support through modular design and partitioning of a knowledge base; static and dynamic constraint checking of slot values and function arguments; and semantic analysis of rule patterns to determine if inconsistencies could prevent a rule from firing or generate an error. Most importantly, CLIPS is maintained as public domain software.

The constructs used in the system are mainly deftemplates, deffacts and defrules. Deftemplates are facts that provide the ability to abstract the structure of a fact by assigning names to each field found within the fact. It is used to create a template which can then be used by non-ordered facts to access fields of the fact by name. The deftemplate fact is analogous to a record or structure definition in procedural programming languages. An example of a deftemplate used in the system is shown in Table 1.

With the deffacts construct, a list of facts can be defined which are automatically asserted whenever the reset command is issued, usually before running the system.

Fig. 2 The most important parts of (**a**) the outer die. (**b**) the inner die



Facts asserted through deffacts may be retracted or pattern-matched, accounting for the fact list continuously changing during run-time. An example of the initialization of the material construct is shown is Table 1. Not every slot of a deftemplate has to be defined.

Rules are defined using the defrule construct. The syntax of a defrule construct is: (defrule <rule-name> <conditional-element> => <action>). The left-hand side is made up of a series of conditional elements which typically consist of patterns to be matched against fact pattern entities. The right-hand side contains a list of actions to be performed when the left-hand side of the rule is satisfied. The arrow (=>) separates the left from the right-hand side of a rule. There is no limit to the number of conditional elements or actions a rule may have. Actions are performed sequentially if, and only if, all conditional elements on the left-hand side

Table 1 Examples of CLIPS constructs

Examples

Deftemplate

```
(deftemplate material
 (slot code (type INTEGER))
 (slot name (type STRING))
 (slot type (type STRING))
 (slot thickness (type NUMBER))
 (slot shear_strength (type
   NUMBER)))
```

Deffacts

```
(deffacts initial
(material (name
 aluminum)
(thickness 1)
(shear_strength
279)))
```

Defrule

```
(defrule material_selection
 (material (name “”))
 =>
 (printout t “ENTER A MATERIAL
  NUMBER:” crlf)
 (printout t “1. Aluminum” crlf)
 (printout t “2. Steel” crlf)
 (printout t “3. Brass” crlf)
 ... .
 (assert (material_selection (read))))
```

are satisfied. CLIPS inference engine attempts to match the rules to the current state of the system and executes the actions. An example of a rule used by the system is shown in Table 1. By the “assert” command, the system creates a non-ordered fact called “material_selection” which holds the number the user has just entered. According to this value the system can then modify the deftemplate “material” and in particular its slot called “name”.

Once a knowledge base (in the form of rules) is built and the fact-list is prepared, the system is ready to execute rules. The agenda is the list of all activated rules, namely all rules which have their conditions satisfied and have not yet been executed. Each module has its own agenda. The agenda acts similarly to a stack, as the top rule on the agenda is the first one to be executed. In CLIPS the knowledge (rules) and the data (facts) are separated and the inference engine essentially applies the knowledge to the data. Inference engine details of CLIPS are presented in [14]. Note that the placement of a rule on the agenda is determined by its salience (priority integer from −10000 to 10000) and the conflict resolution strategy. CLIPS disposes of seven conflict resolution strategies: depth, breadth, simplicity, complexity, “lex”, “mea” and random [14]. The default strategy is depth, meaning that newly activated rules are placed above all rules of the same salience.

4 Expert system development

4.1 Knowledge acquisition

The first step in the development of an expert system is knowledge acquisition. Sources for this step were a variety of sheet metal processing handbooks, theoretical textbooks and empirical knowledge from industrial partners.

Empirical knowledge was acquired by interviews with experts from industry in the field of sheet metal die design in the framework of a funded research program. In the interviews, a series of questions were presented concerning specific aspects of a production problem akin to design methodologies for dies that had already been materialised. In this way, fragments of knowledge were gathered, which the knowledge engineer could associate with each-other after the interview and finally “complete the puzzle”.

Knowledge acquired from theory and technical handbooks was presented by the knowledge engineer to the experts in order to be confirmed or modified by them.

4.2 Building the knowledge base

Knowledge acquisition resulted in the development of a knowledge base of about 500 preliminary rules in natural language termed “crude” rules. These are easy for an active practitioner in the field to understand, but useless to the programmer, who may not have the necessary technical background. The co-operation of knowledge engineer and programmer resulted in the transformation of crude rules into “production” rules following the IF-THEN paradigm. These rules were, then, further studied by the programmer alone to create the proper constructs for the introduction of knowledge into the CLIPS environment. Note that a piece of knowledge that can be described in a seemingly simple sentence is usually not so simple to describe in a coded form. As a result, materializing the system in the CLIPS environment involved more than 2500 CLIPS rules.

Because of the large number of rules, these had to be structured in the knowledge base for better handling. In particular, rules were grouped together according to their technical subject. This resulted in 18 rule pools. Some of the rule pools are used exclusively in a single module of the system, whilst other rules pools are used in more than one modules. Typical rules are presented next for each of the 18 rule pools, whilst details are provided for some rules of the first 3 pools. A full list of the crude rules are presented in [15].

Note that rule triggering flow is controlled by non-ordered facts without slots asserted with the deffacts construct, as explained in Sects. 4.2.1 and 4.2.2 below.

4.2.1 Quality of cut walls

This pool contains 14 crude rules applied in the process planning and finishing modules. They mainly govern the decision of the finishing operation type by handling clearance issues. Note that certain criteria used in other modules can redirect the focus of the expert system back to the process planning module, mostly for the correction of clearance. Two typical rules contained in this production rule pool are the following:

- IF cost is the major factor for choosing operation of hole sidewall smoothing, THEN choose shaving.
- IF accuracy is the major factor for choosing operation of hole sidewall smoothing, THEN choose fine-edge piercing.

These rules are transformed into CLIPS constructs through a question set to the user and coded as a CLIPS rule, see Table 2 (pool 1, rule 1). In the condition part of the rule there are two facts: (finishing (need 1) (wall_percentage ?wp&~0)) and (phase finishing_target). The first slot must have a value of 1, i.e., the system must have already decided that a finishing operation is needed, while the wall_percentage slot must have a non-zero value. The non-ordered slot (phase finishing_target) has already been asserted. The action part of the rule asks the user to set the target for the finishing operation, the answer being stored in the finishing_target_question fact. The phase finishing_target is retracted by the facts list.

According to the value stored in the finishing_target_question fact, the appropriate rules about the finishing operation are triggered. If this value is points to the low cost criterion, the finishing_shaving rule is triggered, see Table 2 (pool 1, rule 2).

In this case, the left-hand side of the rule contains the “finishing_target_question” fact, while the non-zero value of the “wall percentage” slot is still checked. Since the user must have already asked, at an earlier stage, for a certain wall percentage to be uniform, this check is used to actually keep the finishing operation alive in the system, until all parameters of the finishing operation are determined. The rule action is the decision that shaving has to be performed. The non-ordered fact “finishing_target_question” has served its purpose, thus it is retracted. In addition, some useful comments are presented to the user and more non-ordered facts (“shaving_parameters” and “shaving_clearance”) are asserted so that the system can go on and decide on all necessary parameters of the shaving operation.

4.2.2 Clearance

Clearance is strongly related to the quality of cut wall. The 45 rules in this pool deal with estimation, or selection of clearance, according to the edge type required. Each one of the five possible edge types corresponds to different cut sidewall characteristics, see Fig. 3. Rules in this pool apply to the process planning module.

Three typical rules contained in this rule pool are the following:

- Deformation limit is a value for evaluating the possibility of the material deformation and may be used for all sheets thinner than 2.36 mm.
- IF stock thickness <2.36 mm, THEN deformation limit is $f_L = ct\sqrt{S_s}$ where c is the deformation limit constant, t is sheet thickness and S_s is the material shear strength.
- IF f_L>0.3 t, THEN excessive distortion of the cut will occur, plasticity of the material in the area is exhausted and tensile properties are altered.

The first one shows the use and applicability of the deformation limit. The second one gives the formula for its calculation. The third one presents some critical comments to the user, depending on the value of the deformation limit. The rules are implemented in CLIPS as shown in Table 2 (pool 2, rules 1, 2 and 3 respectively). In the first rule, the “DLC” slot holds the value of the deformation limit constant, which is already estimated by other rules of the rule pool. The deformation limit is calculated using the global variables ?*DLC*, ?*t* and ?*Ss*, i.e., deformation limit constant, sheet thickness and material shear strength respectively. The result of the formula is stored in the slot “DL” of the “deformation_limit” fact. The “phase deformation_limit_storage” is a non-ordered fact which will lead to the triggering of the next rule, see Table 2, (pool 2, rule 2). These two rules are grouped together with a third one, see Table 2 (pool 2, rule 3), concerning the case when the deformation limit is larger than 0.3*t. In that case, the user is warned by critical comments and may decide to stop. As can be seen in the right-hand side of the rule, there are no more non-ordered facts, so the system is released from the procedure of estimating the deformation limit.

4.2.3 Force requirements

This pool contains 32 crude rules, dedicated to the estimation of the centre of pressure, cutting force and stripping force, which determine the press tonnage. The necessity of sheared punches is also decided here, accord-

Table 2 Rules examples

Pool	Rule 1	Rule 2	Rule 3
1	(defrule finishing_target_question ?f1 <– (phase finishing_target) (finishing (need 1) (wall_percentage ?wp&~0)) => (retract ?f1) (printout t crlf "MAJOR FACTOR OF FINISHING?" crlf "1. LOW COST" crlf "2. HIGH ACCURACY" crlf crlf) (assert (finishing_target_question (read))))	(defrule finishing_shaving ?f1 <– (finishing (wall_percentage ?wp&~0)) ?f2 <– (finishing_target_question 1) => (retract ?f2) (modify ?f1 (operation shaving)) (printout t crlf " FINISHING OPERATION IS SHAVING" crlf "CRITICAL COMMENTS:" crlf "1. If a PROGRESSIVE DIE is to be used, have shaving separate at the end." crlf......) (assert (shaving_parameters)) (assert (phase shaving_clearance)))	
2	(defrule deformation_limit_estimation ?f2 <– (phase deformation_limit_estimation) ?f1 <– (deformation_limit (DLC ?dlc&~0)) => (retract ?f2) (modify ?f1 (DL (*?*DLC*?*t*(sqrt ?*Ss*)))) (assert (phase deformation_limit_storage)))	(defrule deformation_limit_store ?f1 <– (deformation_limit (DL ?dl&~0)) ?f2 <– (phase deformation_limit_storage) => (retract ?f2) (bind ?*DL* ?dl) (printout t crlf) (printout t "DEFORM. LIMIT"?*DL* crlf) (printout t crlf) (assert (phase deformation_limit_check)))	(defrule deformation_limit_check ?f1 <– (phase deformation_limit_check) (test (> ?*DL* (* ?*t* 0.3))) => (retract ?f1) (printout t crlf "DEFORMATION LIMIT IS LARGE FOLLOWING MAY OCCUR"crlf "1. Excessive distortion" crlf .... crlf))
3	(defrule strip_cut_perc ?f1 <– (force (stripping ?s&~0) (cutting ?c&~0) (strip_cut_percentage ?fp&0)) => (modify ?f1 (strip_cut_percentage(/(*100?s) ?c))))	(defrule strip_cut_perc_check1 (declare (salience 10)) (force (stripping ?s&~0) (cutting ?c&~0) (strip_cut_percentage ?fp&~0) (action nil)) (material (thickness ?t&~0)) (test (and (<= ?t 1) (or (< ?fp 3) (> ?fp 8)))) => (printout t crlf "STRIP/CUT RATIO OUT OF RANGE" crlf "presently this ratio is: " ?fp "%" crlf))	

ing to the loads estimated. This pool is used in the die and press as well as in the tools module.

A typical rule contained in this rule pool is the following:

- Stripping pressure as percentage of cutting pressure can be decided from handbook tables, given the stock thickness.

This rule refers to the stripping pressure to the cutting pressure ratio. There are handbooks that give the acceptable ratios in relation to the sheet thickness. This rule is implemented in CLIPS by performing a simple percentage calculation first, see Table 2 (pool 3, rule 1), and, then, by checking if this percentage is acceptable, see Table 2 (pool 3, rule 1). The first rule is triggered after the stripping force and the cutting force are estimated and stored in the respective slots of the "force" fact. The right-hand side estimates the force ratio and changes the zero value of the respective slot. The second rule relates the force ratio to the sheet thickness. If stripping/cutting force ratio is out of range, the system will lead to ways to overcome this problem, such as the use of stage punching or sheared punches.

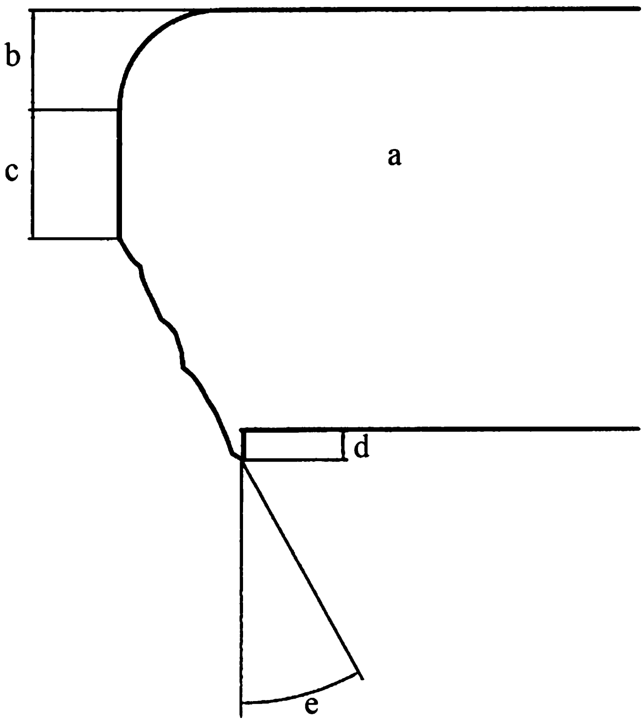


Fig. 3 Cut sidewall characteristics that can be predicted by the five typical edge types: **a**. Sheet, **b**. Rollover depth, **c**. Burnish depth, **d**. Burr height, **e**. Fracture angle

4.2.4 Punches

The 28 rules of this pool are exclusively used for deciding the punch and bushings parameters. Slenderness ratio is used to decide on stage punching. This pool is drawn upon by the Tools module. Typical rules contained in this rule pool are the following:

- IF material is aluminum OR brass OR carbon_steel AND sheet thickness is thicker than 6.35 mm AND production run is up to 100000 pieces THEN punch material should be Water-hardened tool steel W2.
- IF punch geometry is irregular OR punch face area is ground to an angle, THEN for these punches use heels for guidance.

4.2.5 Dies

There are 20 rules in this pool, referring to single operation, compound and progressive dies, and used mostly in the die and press module to decide the most suitable type of die for the operation. Two typical rules read:

- IF high accuracy piercing is needed, THEN use single operation die
- IF for certain holes, relative position accuracy is needed, THEN make these holes in the same station of progressive die.

4.2.6 Accuracy

There are 10 rules in this pool, mostly used by the die and press module to decide the best type of die for the operation. Some of them can also be called by the process planning module. Two typical rules read:

- IF accuracy on hole location has to be increased, THEN use a rigid stripper, precisely aligned on guideposts to guide the punches
- IF drill bushings are used as guides THEN typical clearance of round punches in the stripper is 0.005 mm–0.013 mm.

4.2.7 Hole spacing

This pool serves the process planning module. Most of the 14 rules in total are used to estimate minimum dimensions allowed on the sheet. Typical rules read:

- IF stock thickness <0.813 mm THEN set (minimum distance of square OR rectangular cut from the edge)= (minimum distance of pierced hole from a NOT straight edge)=1.527 mm.
- IF smaller distance than (minimum distance of pierced holes from an edge) is demanded, THEN the hole may be cut through the edge in a keyhole shape that minimizes bulging and also doesn't leave sharp points.

4.2.8 Piercing holes at an angle

This pool includes rules referring to the special case of holes cut by inclined punches. It is used by the tools module. Typical rules read:

- IF holes at a great angle to the stock surface are to be pierced, THEN securely clamp the workpiece to the die with pressure pad AND use punch ground with a step
- IF holes at a great angle to the stock surface are to be pierced, THEN the die is usually ground to fit the contour of the part.

4.2.9 Rule pools used exclusively by the Finishing module

The shaving rule pool contains nine rules used by the finishing module. The facts asserted by these rules can fire rules in other pools and modules, such as process planning and tools. Two typical rules read:

- IF single shaving operation is used, THEN the hole will have a straight edge to 75% of metal thickness
- IF there is shaving operation, THEN put it in a separate phase from piercing OR in a separate station of a progressive die.

The following are the typical rules of the deburring pool:

- IF minimization of burrs is needed, THEN use proper punch to die clearance
- IF burr removal is needed (general case) THEN use grinding.

4.2.10 Fine-edge piercing

Fine-edge piercing is a finishing operation, thus the respective rules apply to the finishing module. In many cases, though, focus is transferred to other modules, such as die and press module. A typical rule reads:

- IF process is fine-edge piercing AND material thickness is over 3.175 mm OR material is alloy steel THEN sharp corner and fillet radii should be avoided. Prefer radii of 10% to 20% of stock thickness.

4.2.11 Rule pools applicable exclusively to the Tool module

There are 40 rules in the die shoes pool concerning the upper and lower die shoe. Typical rules are:

- IF there are no large openings in die shoe, THEN use semi-steel, because they crack under press-induced operational stresses on the die.
- IF there are large openings in die shoe (e.g., for blank removal), THEN use all-steel die set.

A typical rule, among the 13 contained in punch shank and guideposts rule pool, are the following:

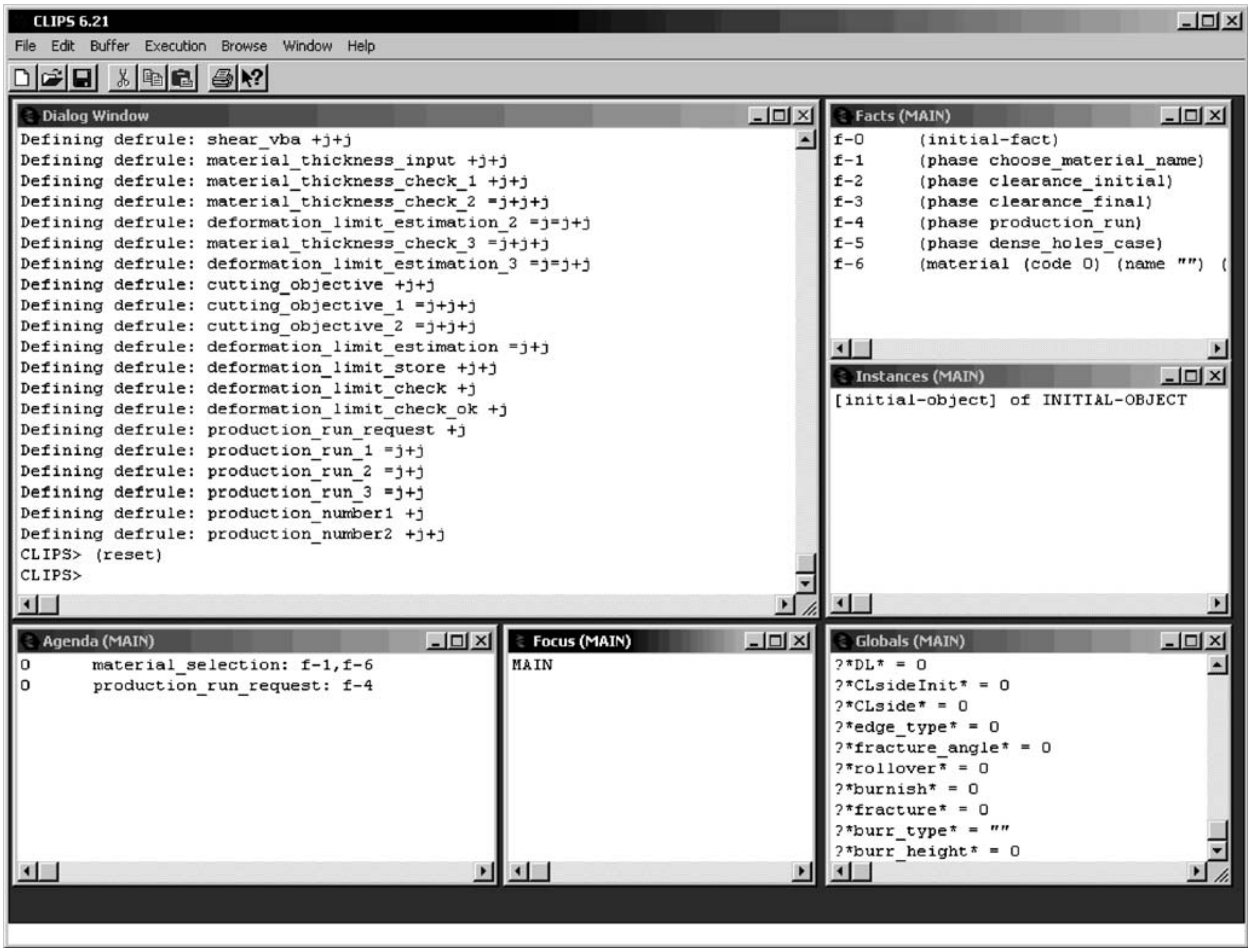
- IF more than 2 back guideposts are used, THEN guideposts must be of the type: removable

A typical rule in the guided strippers pool, read:

- IF hardened plate is necessary AND run is long AND die is carbide OR D2 OR D4, THEN stripper plate material is O1 OR A2 at Rockwell C50 to 54

A typical rule in the pilots or locator pins rule pool reads:

- Pilots are longer than any punches in the same stroke.



```
Defining defrule: shear_vba +j+j
Defining defrule: material_thickness_input +j+j
Defining defrule: material_thickness_check_1 +j+j
Defining defrule: material_thickness_check_2 =j+j+j
Defining defrule: deformation_limit_estimation_2 =j=j+j
Defining defrule: material_thickness_check_3 =j+j+j
Defining defrule: deformation_limit_estimation_3 =j=j+j
Defining defrule: cutting_objective +j+j
Defining defrule: cutting_objective_1 =j+j+j
Defining defrule: cutting_objective_2 =j+j+j
Defining defrule: deformation_limit_estimation =j+j
Defining defrule: deformation_limit_store +j+j
Defining defrule: deformation_limit_check +j
Defining defrule: deformation_limit_check_ok +j
Defining defrule: production_run_request +j
Defining defrule: production_run_1 =j+j
Defining defrule: production_run_2 =j+j
Defining defrule: production_run_3 =j+j
Defining defrule: production_number1 +j
Defining defrule: production_number2 +j+j
CLIPS> (reset)
CLIPS>
```

```
f-0      (initial-fact)
f-1      (phase choose_material_name)
f-2      (phase clearance_initial)
f-3      (phase clearance_final)
f-4      (phase production_run)
f-5      (phase dense_holes_case)
f-6      (material (code 0) (name "") (
```

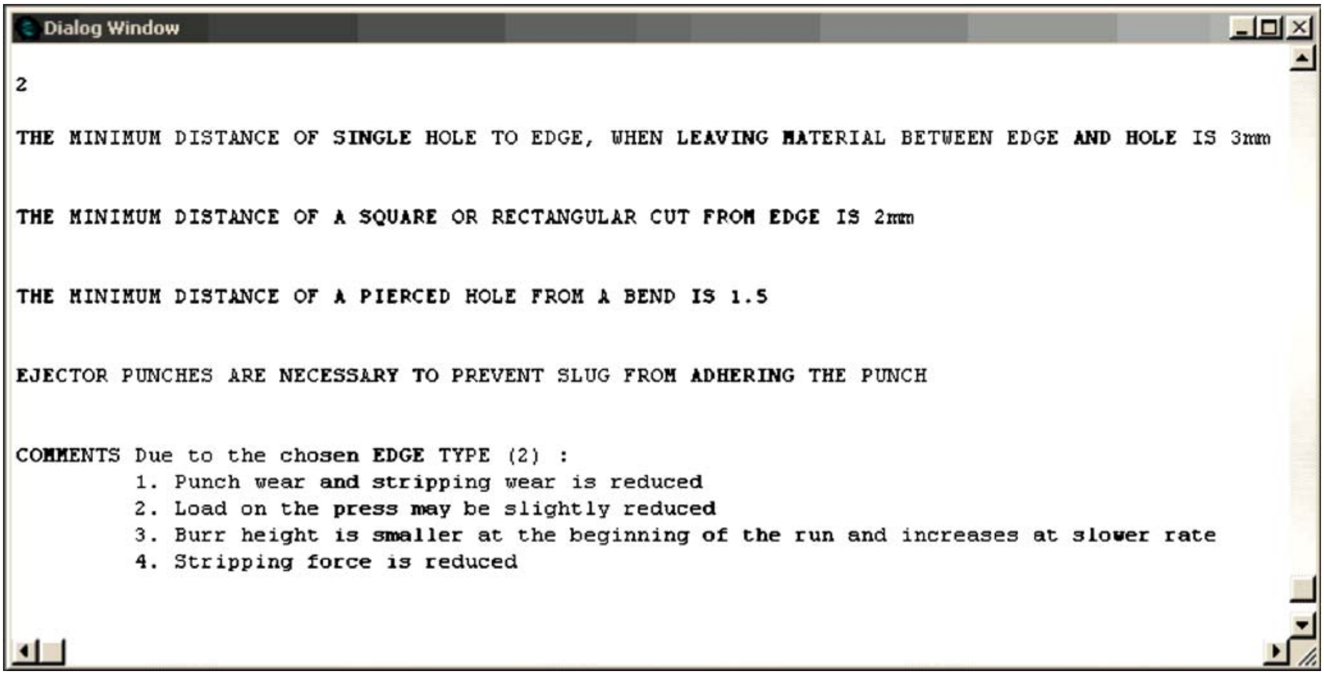
```
[initial-object] of INITIAL-OBJECT
```

```
0      material_selection: f-1,f-6
0      production_run_request: f-4
```

```
MAIN
```

```
?*DL* = 0
?*CLsideInit* = 0
?*CLside* = 0
?*edge_type* = 0
?*fracture_angle* = 0
?*rollover* = 0
?*burnish* = 0
?*fracture* = 0
?*burr_type* = ""
?*burr_height* = 0
```

Fig. 4 The multi-window CLIPS environment. An initial instance is presented, when rules are buffered



```
2

THE MINIMUM DISTANCE OF SINGLE HOLE TO EDGE, WHEN LEAVING MATERIAL BETWEEN EDGE AND HOLE IS 3mm


THE MINIMUM DISTANCE OF A SQUARE OR RECTANGULAR CUT FROM EDGE IS 2mm


THE MINIMUM DISTANCE OF A PIERCED HOLE FROM A BEND IS 1.5


EJECTOR PUNCHES ARE NECESSARY TO PREVENT SLUG FROM ADHERING THE PUNCH


COMMENTS Due to the chosen EDGE TYPE (2) :
         1. Punch wear and stripping wear is reduced
         2. Load on the press may be slightly reduced
         3. Burr height is smaller at the beginning of the run and increases at slower rate
         4. Stripping force is reduced
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Fig. 5 The dialog window. This instance presents important comments exported on screen

A typical rule in the guide bushings rule pool reads:

- IF no great stripping force is expected, THEN the head of the bushings are oriented around the stripper's upper surface

A typical rule in the knockouts and knockout pins rule pool reads:

- IF operation is forming OR drawing OR blanking THEN use knock-out pins

A typical rule contained in the punch plate rule pool, containing seven rules in total, reads:

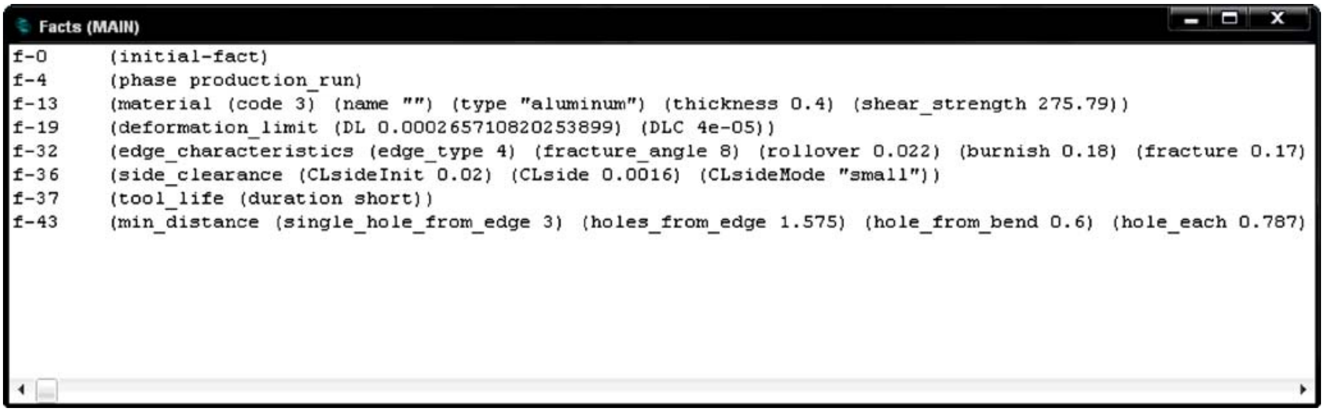
- IF operation is blanking OR piercing AND die plates or die parts hold inserts AND stock material is soft AND thin, THEN die plates and die parts should be of cast iron OR low carbon wrought steel.

5 System use and results

5.1 Execution

The system runs in a multi-window environment, which allows the user to monitor all running processes, see Fig. 4. For instance, the focus window shows the current module and the globals window presents the global variables used and their current values.

In the dialog window all run-time information is displayed and the system-user interaction takes place. This is where the user is asked all necessary information, and also messages concerning potential problems are presented, see Fig. 4. When a slot of a fact is filled, this information



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f-0      (initial-fact)
f-4      (phase production_run)
f-13     (material (code 3) (name "") (type "aluminum") (thickness 0.4) (shear_strength 275.79))
f-19     (deformation_limit (DL 0.000265710820253899) (DLC 4e-05))
f-32     (edge_characteristics (edge_type 4) (fracture_angle 8) (rollover 0.022) (burnish 0.18) (fracture 0.17)
f-36     (side_clearance (CLsideInit 0.02) (CLside 0.0016) (CLsideMode "small"))
f-37     (tool_life (duration short))
f-43     (min_distance (single_hole_from_edge 3) (holes_from_edge 1.575) (hole_from_bend 0.6) (hole_each 0.787)
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Fig. 6 The facts window: an instance with a number of facts asserted and slots filled. The name of every fact is as close to its technical meaning as possible

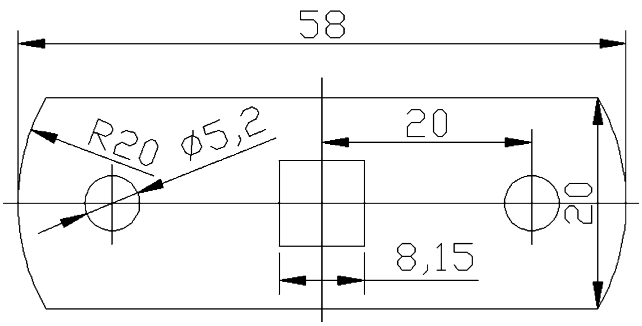

Fig. 7 The product studied in case 1

might be useful to the user at run-time, this piece of information is displayed in the dialog window, see Fig. 5.

In addition, there are other windows which help the advanced user to fully monitor the system. The most important are the aagenda window, where the user can see the triggered rules, in the order in which they will be fired. The facts window displays all asserted facts, see Fig. 6. During run-time, the user can browse in this window for the current value of a particular slot of a fact. Every effort was made to keep fact and slot names close to their technical meaning. The facts window appeals mostly to the sheet metal expert, since it contains all technical outcome of the system. This information is also displayed in the dialog window during run-time along with critical comments. Furthermore, if the system considers that the sheet metal operation cannot succeed or the desired final geometry cannot be achieved, it will halt and display in the dialog window the possible reasons and ways to overcome the problem.

5.2 Results

Two test cases are presented. The part concerned in the first test case is presented in Fig. 7. The sheet material is half-hard aluminum (168 MPa shear strength), 1.2 mm thick. The production run is 1000 pieces. All three cuts have to be accurate, as far as their dimensions are concerned. It is also required to have at least 50% uniform cut surface, which indicates that a finishing operation might be useful. Results obtained are summarised in Table 3.

The part concerned in the second test case is presented in Fig. 8. The sheet material is full-hard aluminum (279 MPa

Table 3 Results for test case 1

Modules			
Process panning	Die & press	Tools	Finishing
Clearance per side: 0.036 mm	Cutting force: 1.34 tn	Use standard quill punches. Punch material should be high-speed steel M2 (0.8%C, 4% Cr, 5%Mo, 6%W, 2%V)	The finishing operation chosen for this case is shaving.
Cut details expected Fracture angle: 8°	Stripping force: 164 kg. It is out of range, thus sheared punches are necessary	For extra guidance four-pillar die set and ball bearing or self lubricating bushings can be used	For this operation replaceable inserts are recommended,
Rollover depth: 0.06 mm	Minimum distance of holes to the sheet edge: 3 mm	Bushings material should be Water-hardened tool steel W1 (0.6% to 1.4% C).	shaving clearance should be 0.15 mm
Burnish depth: 0.54 mm	Minimum distance of square cut to the sheet edge is 2.4 mm	Minimum slenderness ratio is 1 Minimum punch length: 16 mm	one phase shaving operation can be used
Fracture depth: 0.5 mm	To keep the cost as low as possible use single operation die	Punches should be tempered to 62Rockwell	In case of progressive die, shaving operation should be in a separate station after cutting
Medium and compressive burr	Progressive die can also be used by spreading cuts in 2 phases.	Punch plate should be about 12 mm thick	In case of single operation die, shaving operation should be made in a separate phase
Tools life is expected to be shortdue to small clearance used		Use of semi-steel die set for the die shoe, otherwise cracks may occur due to operational stress	
All cuts can be made in one phase		Punch shank can be cast along with the shoe and machined to size afterwards	
		Hard chromium-plated steel is recommended for guideposts.	
		Guideposts can be embedded in lower die shoe	
		Use knockout pins close to punches and a spring loaded knockout plate to mount them.	

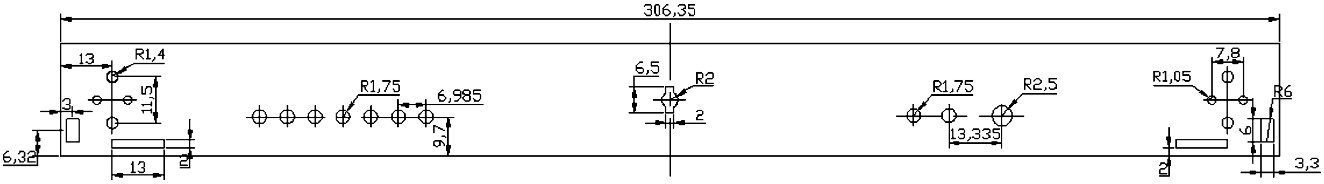

Fig. 8 The product studied in case 2

shear strength), 1 mm thick. The required production run is 10000 pieces. There are no special demands for accuracy in this product. The results obtained are summarised in Table 4.

In the first test case execution time was about 310 sec in a 1.8 GHz Pentium machine, whereas in the second test case execution time was about 570 sec.

The results were considered by the industrial experts that helped to build the knowledge base to be directly acceptable and to reflect accurately the knowledge coded in the system.

6 Concluding remarks

In this work an expert system for die design and process planning of cutting and piercing operations was developed. It is based on a sizable knowledge base of production rules and consists of five modules.

The aim of the system is to help both the designer and the manufacturer in the modern sheet metal industry become more efficient. The new product designer can get help on the production feasibility (manufacturability), while the manufacturer can receive advice either on the hardware needed or on the process plan before even thinking about production. In this way, the system helps reducing the time needed for a new part production, by reducing the time spent on design corrections and by delivering to the manufacturer many pieces of information needed for the die construction.

The expert system shell CLIPS was used for the first time to materialise a system focused on manufacturing. Although the CLIPS environment looks rather user-unfriendly at first glance, it proved to be a very reliable and “smart” tool for the expert system programmer.

The knowledge acquisition and elicitation process made use of three types of rules: so-called crude rules, expressed in natural language, production rules of the familiar IF-THEN type and CLIPS rule constructs which are more generic, in that even questions to the user can be expressed in this form. The knowledge engineer has to transform crude rules into production rules. The programmer, with occasional help from the knowledge engineer, should transform production rules to CLIPS constructs.

Table 4 Results for test case 2

Modules		
Process planning	Die & press	Tools
Clearance per side: 0.1 mm	Secondary shear will be produced during cutting operation due to the predetermined clearance	Ejector punches are necessary to prevent slug from adhering the punch
Cutting force: 0.94 tn	Due to small clearance the stock material sticks to the punch at burnish area, thus large forces are needed to move the slug through the die for ejection	Conventional punches can be used
Stripping force: 69.5 kg.	Large stripping forces are needed to remove the metal left around the punch	Recommended punch material is high-speed steel M2 (0.8%C, 4%Cr, 5%Mo, 6%W, 2%V)
Fracture angle: 9°	Slug might be welded into the die cavity	Minimum slenderness ratio: 2.5
Rollover depth: 0.07 mm	Single operation die is recommended	Minimum punch length: 16 mm
Burnish depth: 0.325 mm		Punch plate thickness 24 mm
Fracture depth: 0.55 mm		Recommended punch bushing is material water-hardened steel W1
Normal and tensile burr		Use all-steel die set for the die shoe
Minimum distance between cuts 1.21 mm		Guideposts material should be hardened centerless ground steel
Minimum distance of single hole to the sheet edge: 3 mm		Stripper material should be medium carbon steel (like 1020 or 1035)
Minimum distance of rectangular cut to the sheet edge: 2 mm		Use shoulder bushings for guideposts
All cuts can be made in one phase		

Rules are practically structured into rule pools, according to natural coherence criteria as dictated by the “mechanics” of the particular problem. This involves definition of the major aspects that have to be tackled, e.g., clearance, type of die, finishing operation etc., in which intermediate decisions concerning influential factors have to be made before comprehensive decisions are arrived at.

On the other hand, the knowledge domain and the comprehensive decisions can be structured conceptually into five different areas, termed system modules, pertaining to the problem, which, at first, can be regarded as independent from each other. Each rule pool feeds one or more of these modules, which indicates that modules in reality are not quite as independent from each other.

A natural continuation of the work involves obtaining automatically from product model databases as much as possible of the information which at present is fed by the user. This is already under way using a feature-based CAD product model representation.

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