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Simulation and Knowledge Based Process Planning of Multi-Step Sheet Forming Processes

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Abstract

The application of the methods of Computer Aided Engineering in sheet metal forming is looking back for several decades. It covers a wide range of activities from the product design through the process planning and process control including sophisticated methods of modelling and simulation. Among the CAE activities, recently the development of Knowledge Based Systems has become an emerging field. Most of the available Knowledge Based Systems are based on simplified plasticity theory and empirical technological rules. Therefore, they are usually not able to give accurate solutions and reliable predictions for complicated forming processes. In the last two decades, significant progress has been also achieved in the numerical modelling of forming processes. In spite of the enormous development of hardware and software facilities, the exclusive use of numerical modelling still seems to be very time- and cost consuming. Therefore the integration of these two fields has great practical importance. In this paper, the challenges and opportunities of the integration of Knowledge Based Systems and Finite Element Modelling in the process planning of multi-step sheet forming processes will be given.

Keywords: sheet metal forming, knowledge based systems, FEM simulation

1. Introduction

In the recent years, the role and importance of metal forming processes in the manufacturing industry have been continuously increasing primarily due to its material- and cost-effective nature. It is further emphasised by the recent advances in tools, materials and design, which in turn provide significant improvements in the mechanical properties and tolerances of the products. It is also characteristic for metal forming processes that the final shape of the component cannot be produced generally by a single operation, but more often several operations should be performed to transform the initial simple geometry into a more complex product. Moreover, in the recent years metal forming evolves in the direction of net-shape or near-net-shape manufacturing to reduce the need for subsequent machining operations and to minimise the total manufacturing cost. Consequently, the process planning in metal forming represents a very important and complex task. The global competition also requires that manufacturing industry – besides the skill and the experience accumulated in the shop practice – should increasingly utilise practical and proven techniques of Computer Aided Engineering for rapid and cost effective process design and tool manufacturing.

Recently, there are two main approaches to achieve these goals. One of them is the application of knowledge-based expert systems, which are generally based on simplified plasticity theory and empirical technological rules. There are a great number of papers dealing with the use of knowledge-based systems in sheet metal forming [1]. But the exclusively knowledge based solutions have certain disadvantages: they usually cannot provide an enough accurate solution to the problem since these systems are generally based on simple technological rules with limited validity. Therefore knowledge-based systems cannot predict for example the material flow, and usually cannot provide the accurate stress and strain distribution within the component.

As another approach, numerical techniques (mainly finite element modelling) are applied for the analysis of the plastic deformation. The main objectives of the application of numerical process simulation in metal forming are to determine appropriate process parameters and to develop adequate die design by process simulation, to improve part quality by predicting process limits and preventing flow induced defects. Besides these, numerical process simulation also leads to reducing process and dies try-out, as well as shorter lead times, while significantly reducing manufacturing costs [2]. But the exclusive use of numerical modelling has some drawbacks, too. In spite of the enormous development of hardware and software facilities, the numerical modelling still seems to be very time- and cost consuming and the reliability of results is often dependent on the experiences of the user. It is partly due to the large number of operating parameters whose influence should be investigated, and partly due to the numerical difficulties caused by the complexity of the applied mathematical model to describe the material behaviour.

Therefore, the integration of these two fields (i.e. the knowledge-based systems and numerical modelling) has gained primary importance. Since the knowledge-based systems are mainly based on technological rules they are very appropriate to support the process engineer to determine various alternative process plans and to analyse them from the technological point of view. Using the knowledge-based systems as a first process-planning tool, the user can easily determine technologically feasible process plans. The numerical methods then can be used to provide deeper and theoretically more accurate analysis of stresses and strains, flow parameters, die-cavity filling and loads. In these solutions, the integration is mainly limited to the process planning part of the product development cycle. Numerical simulation and modelling of forming processes based on the knowledge of physics of forming process and validated by experimental results and technological experiences, may be regarded as the most powerful tool for optimising process plans and process parameters. This integrated solution can significantly reduce – and in many cases eliminate – a full-scale process trial which was for a long time very characteristic for the metal forming industry. By this virtual design and manufacturing both the development time and the costs can be radically decreased comparing to conventional industrial practice.

In sheet metal forming, modelling and simulation can be used for many purposes, e.g. to predict material flow, to analyse stress-, strain and temperature distribution, to determine forming forces, to forecast potential sources of defects and failures, to improve part quality and to reduce manufacturing costs. Nowadays, modelling and simulation are often integrated parts of product and process design in an integrated manufacturing environment. It is very essential to apply modelling and simulation in the design phase: though design costs are usually between 5 to 15 percent of the total production costs but the decisions made in this early stage significantly determine the overall manufacturing costs, as well.

In simulation, several parameters and influencing factors should be considered. Material properties and constitutive laws, tribological and frictional conditions are of significant importance, but geometrical representations and computational time should also be considered for a cost effective and reliable numerical modelling and simulation in sheet metal forming.

2. State of the Art in Metal Forming

To understand the development route leading to the need for integration of knowledge-based systems and numerical modelling, first the evolution of knowledge-based systems and their application in various forming processes will be shortly overviewed. Then the present state of the art of numerical simulation in metal forming and the challenges and opportunities of their integration into knowledge-based systems will be described.

2.1. Commercial CAD/CAM/CAE Systems and Knowledge Based Systems

Most of the commercial CAD systems may be regarded as *geometric (graphical) systems*, which basically store only geometric information on the component geometry. They usually provide good possibilities for product design with flexible modification and fast documentation, but significantly less support for engineering analysis. Recent developments in this field resulted in good interfaces with mechanical analysis systems; for example they are able to generate finite element mesh in good quality and exporting it in appropriate format to the supported analysis system. But if the links to manufacturing and process analysis related functions are considered the situation is still not satisfactory in these systems.

The so-called dimension and constraint driven parametric and variational CAD systems provide better basis for satisfying the requirements of process analysis. Therefore CAD systems used in knowledge-based systems are based on the so-called “*feature concept*” which facilitate to group geometric and non-geometric information in an *object-oriented part model*. If we consider a knowledge-based system with the main aim of generating feasible process plans, those geometric information that are necessary for geometric reasoning are absolutely essential. That is the main reason for integrating object-oriented, feature-based geometric modelling into knowledge-based systems used in metal forming processes.

2.2. Knowledge Based Systems in Sheet Metal Forming

Sheet metal forming is one of the most widely applied manufacturing processes in the manufacturing industry. Parts made from sheet metal can provide, with appropriate design, a high strength to weight ratio. They are increasingly used from small electrical components through the automobile industry up to the large aircraft structures for various purposes. Despite the increasing number of applications of sheet metal parts, with the exception of well-known handbooks, surprisingly little quantitative design information of a general nature is available in the technical literature. Most companies use internal guidelines for part design, based on experience with the geometries and materials used in that specific company. While such design guidelines are extremely useful and practical, they do not necessarily consider in detail the fundamental reasons for selecting a given design. Thus, when a new part, a new material, or a new process is introduced the entire set of experience-based design guidelines must be re-evaluated and modified. Therefore, it is necessary to develop generic design methods based on metal forming analysis and on systematic experimental investigation. This tendency can be clearly observed in the development of various knowledge-based systems for designing sheet metal parts and for process planning of forming procedures. As in many other metal forming applications, process planning and design of dies for sheet forming can benefit from a combined application of knowledge based systems and process modelling. Recently, many companies are applying CAD/CAM techniques and knowledge-based expert systems to improve and partially automate die design and manufacturing function.

Several program packages were also elaborated for sheet metal forming processes at the University of Miskolc at the Department of Mechanical Engineering. They can be regarded as part of a complete system for metal forming. Within this systematic development various program packages have been elaborated. Among them first a general CAD/CAPP/CAM system for the process planning of sheet forming processes performed in progressive dies should be mentioned [3]. In this system, the process planning and the die-design functions are integrated into a knowledge-based expert system. It consists of a *geometric module* for creating, exporting and importing the object geometry, a *blank module* for determining the optimum shape, size, and nesting of blanks, a *technological design module* for designing the process sequence based on empirical rules and technological parameters, a *tool design module* for designing the tools and selecting a tool of standard size, and an NC/CNC *post processor module* for preparing programs for NC/CNC manufacturing of tool elements.

Another knowledge-based expert system was developed for the process planning of deep drawing [4]. In this system, the process-planning module is divided into two main parts: a so-called geometrical process planning and a technological process-planning sub-module. In the geometrical process planning module a so-called geometrically possible process plan is generated automatically by recognising the main geometrical shapes of the component to be drawn which is further refined in the second sub-module by taking the technological (formability) limitations into consideration. This latter sub-module is based on a simplified plasticity theory and experimental technological formability data. In the research work presented in this paper, this KBS system is applied and it will be described in more detail in subsequent sections.

2.3. Finite Element Simulation in Metal Forming

Nowadays, computer aided simulation – particularly finite element modeling – of various manufacturing processes is widely applied not only in academic research but more and more as an everyday tool in industrial practice, too. The application of efficient and accurate simulation codes can provide significant advantages, for example: elimination of expensive experimental trials, shorter lead times, more reliable results and even better product quality. Computer simulation of sheet metal forming has already been successfully implemented in many stamping related industries, particularly in the automotive industry [5].

Newest generation of simulation packages provide solution for the whole sheet metal forming chain from the conceptual design of products, through process planning and die-making, up to the final process validation and tuning. These complete solutions can be found already in most of the software packages of leading finite element simulation code providers, and even very similar approaches can be observed concerning the offered solutions for certain research tasks [6].

In the former years, research activities in Finite Element Modeling of manufacturing processes mainly focused on individual processes. Obviously, it was of great theoretical and practical importance from the viewpoint of evolution of modeling and simulation, and also considering its industrial application. However, in recent years, research focus has shifted from the initial objective (in sheet metal forming often restricted to "simple" formability analysis) to global quality control and an overall process integration.

Therefore, in manufacturing industry, it is absolutely essential to include the entire process chain in simulations in an integrated virtual environment [7]. These requirements were strongly supported by new innovative forming processes, for example, forming of tailor-welded blanks [8], hydroforming, etc., and they are absolutely essential for multi-stage forming processes [9], too.

This integration in simulation procedures is even more important in those processes where intermediate heat-treatment is included between the manufacturing phases. In this paper, the possibility of coupling FEM codes in forming and heat-treatment simulations to create an integrated virtual simulation environment for the whole process chain will be described.

3. Simulation and Knowledge Based Systems: An Integrated Approach

Recently there are several efforts to develop systems for metal forming with *full integration* of knowledge-based solutions and FEM simulation. In this case, the simulation is integrated into the whole development process, i.e. the numerical simulation is an inherent part of the development cycle from the conceptual-product design, through the process planning and die design. Therefore this kind of concept is often termed as Simulation Based Design. This concept provides a complete virtual design and manufacturing environment.

Since in former years, we have developed several Knowledge Based systems for sheet metal forming applications to support the work of design and process engineers in industrial circumstances, our *Simulation and Knowledge Based* system is based primarily on these solutions.

In this paper, the results of this research activity will be described through the example of a real industrial problem.

3.1. Process planning of multi-step forming processes using the Knowledge Based approach

The industrial problem selected to illustrate the process planning applied in multi-step deep-drawing processes is the production of a car audio load-speaker frame shown in Fig. 1.

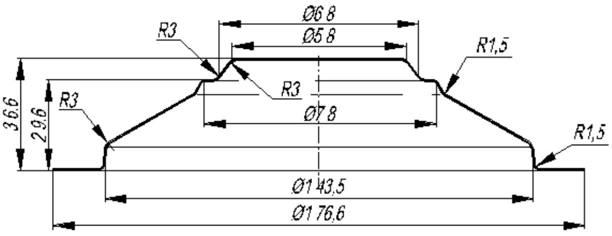

Fig. 1**.** Geometry of the component to be produced with multi-step sheet forming

The material is a mild steel of deep-drawing quality. A primary process plan was generated by a Knowledge Based Expert System – called *DEEPEX* – developed for deep-drawing of axisymmetric components at the Department of Mechanical Engineering at the University of Miskolc [10]

The system is based on a feature-based, object oriented geometric description of the component to be drawn. In this system, a two-stage process planning strategy is applied. In the first stage, the system is capable to generate an initial – so-called *geometrical process sequence*. This task is based on the principles of group technology, and it is done by an automatic shape and feature recognition processing. This is purely a geometry based first pass not considering any technological constraints. This is illustrated in Fig.2, where a geometrically feasible process plan is shown. As it can be seen from Fig. 2, this geometrically feasible process plan contains four drawing stages mapping the main surfaces of the compont to be drawn.

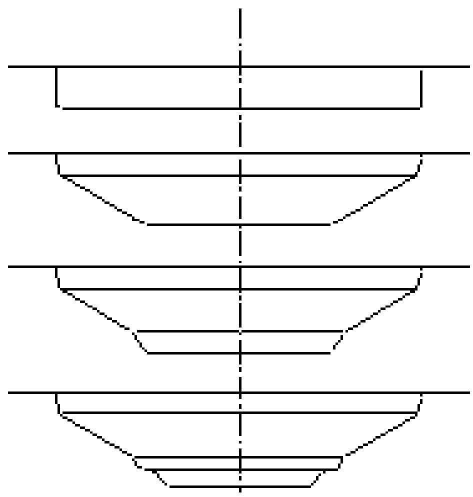

Fig.2. Geometric process plan generated by the Expert System called *DEEPEX*

On the basis of the geometric process plan, a technologically feasible process plan is generated. When generating this technological process plan, the formability constraints are taken into consideration by the system. This is based on simple plasticity theory and on conventional technological parameters (e.g. limit draw ratios, permitted cumulated deformation, etc.). A technologically feasible process plan is shown in Fig. 3.

It can be seen from this figure that technologically also

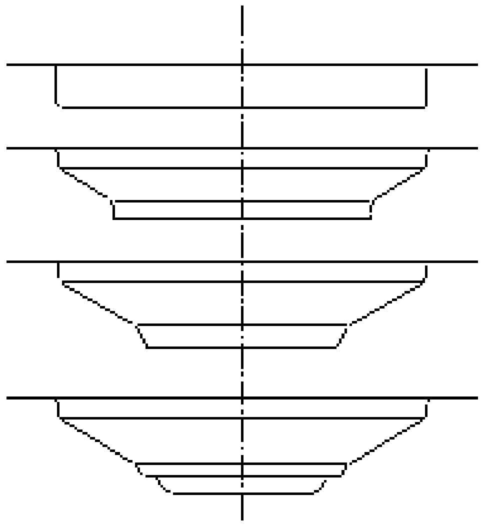

Fig. 4. The first technological variant prepared by the Expert System

four drawing steps are required, but concerning the drawn diameters in each stages, they are somewhat different from that of the geometric process plan. The first step is the same, as proposed in the geometric process plan. However, in the second step, the conical surface cannot be created fully, since it would require larger drawing ratio than it is permitted for the given material in a redrawing stage. Therefore, an intermediate cylindrical surface with the diameter d = 100 mm is drawn in this stage. The conical surface is completed in the third step, when simultaneously, the next surface with the diameter d = 78 mm is drawn. The deep-drawing of the entire component is completed in the fourth step when the smallest diameter (d = 58 mm) is

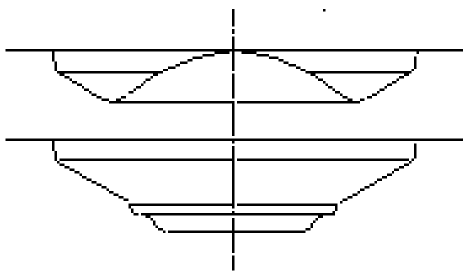

Fig. 3. Modified technologically feasible process plan applying reverse drawing

drawn.

In Fig. 4, an alternative process plan can be seen: in this case, the first two drawing stages are substituted by a reverse redrawing stage (i.e. two drawing steps are merged into one, properly designed reverse drawing process). During the reverse drawing process, the material needed for the subsequent drawing operations is accumulated in the semi-spherical dome surface. Due to this forming solution, a very efficient concentration of the forming operations may be realized: in the next step, the subsequent two diameters (d = 78 mm and d = 58 mm) can be drawn in one drawing stage. With this solution, the deep-drawing of the component can be completed altogether in two drawing steps providing a very efficient concentration of forming operations.

Obviously, in these process plans only the deep-drawing operations are shown, but to produce the component shown in Fig. 4., further operations (trimming, piercing, flanging) are also required. These operations will be also discussed with the simulation results.

3.2. *Verification of Knowledge Based Process Planning Using Finite Element Simulation*

As it was mentioned before, one of the main disadvantages of knowledge based solutions that they are based on simple plasticity theory and conventional technological parameters, thus they do not provide an enough accurate solution: they cannot predict, for example, the material flow, or detailed stress- and strain distribution. Therefore, particularly in those cases, when technological processes are close to the limit values, it may be critical whether the process plan really provides defect-free solution in any case. In these cases, the integration of numerical simulation into the process planning to verify and confirm the results gained from the Expert System may be regarded as the most appropriate solution to provide theoretically reliable solutions.

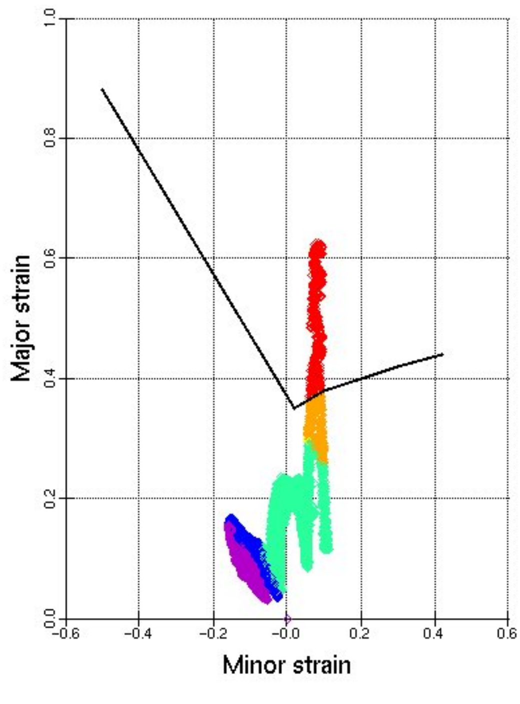

Fig. 5. Forming limit diagram for the 1^{st} techno-logical variant after the 3^{rd} drawing step

In our case, the numerical simulation of both technological process plans was performed using the AutoForm finite element code. The geometric description applied in the Expert System can provide the necessary input data for the discretization of the component. The geometric data is exported in IGES file format. In the FEM simulation, the material of the component to be drawn is handled as an anisotropic, elasto-plastic shell material (applying Hill's anisotropic plasticity algorithm). The tool materials in this analysis are taken as perfectly rigid.

In Fig. 5, some results of the multi-step forming simulation can be seen for the first technological process sequence shown in Fig. 3. The first simulation went through several trials by modeling. In the first run, an extra thinning can be observed in the last drawing stage. It can also be well seen from the forming limit diagram including the total strain path for the 3rd forming step (Fig. 5.).

It is worth mentioning that an even more severe rupture appeared on the drawn part after the piercing operation which follows the last drawing step. This rupture occurred in the zone where the extra thinning can be observed after the third drawing step. It indicates the significance of the residual stresses, which lead to the appearance of these cracks during the piercing operation.

Therefore, in the next simulation run, an intermediate heat-treatment was applied between the second and third drawing stages. Applying a full recrystallization annealing, the strain-hardening is eliminated and the mechanical properties are restored to their original values (i.e. the mild, non-deformed state). In this case, there is no any crack during the drawing processes; all parts of the component remain in the safe zone (see Figure 6).

However, it should be noted that this production procedure including four drawing stages and an intermediate heat-treatment, can be considered as a very expensive and time consuming process plan.

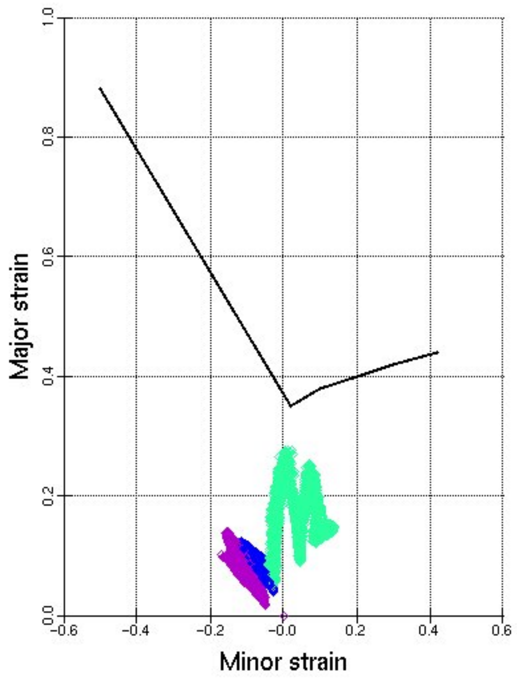

Fig. 6. Forming limit diagram for the 2nd technological variant

In the next simulation trial, the second technological alternative process plan (shown in Fig. 4) was applied. In this case, the first two drawing stages are merged into one, properly designed reverse drawing process.During the reverse drawing process, the material needed for the subsequent drawing operations is accumulated in the semi-spherical dome surface.

Analyzing the plastic strain history drawn into the forming limit diagram (Fig. 6) clearly shows that this solution will result in a robust and safe forming procedure: the plastic strain remains in the safe zone for the total forming process and the thickness changes are also less significant.

The total process plan including the additional (i.e. trimming, flanging, piercing) operations is shown in Fig. 7.

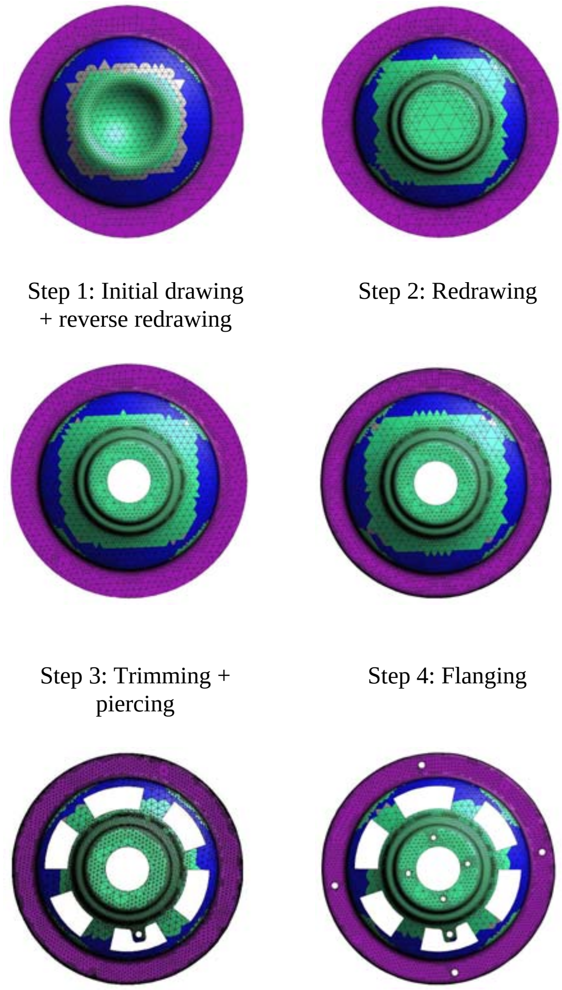

Fig. 7. Simulation results of the 2nd technological variant including all operations

4. Experimental verification

The second process plan was experimentally verified. The drawing experiments were performed on a double-action hydraulic press with a nominal capacity of 400 kN. The blank was cut from a strip-coil with 200 mm width. The calculated blank diameter was 196 mm.

During the experimental verification, a two-hundred piece series was produced. These experiments confirmed the suitability of the proposed process plan. This so-called pilot-series production was successfully performed. A series of components in the order of the process sequences including also the trimming, flanging and piercing operations is shown in Figure 9.

Fig. 8. The experimental production series

5. Summary - Conclusions

In this paper, an integrated application of a Knowledge Based Expert System (*DEEPEX*) with Finite Element Simulation was analyzed through the example of a multi-stage forming process of a car audio loudspeaker frame. On the basis of the presented example, it may be stated that the integrated application of Knowledge Based Systems and Finite Element Simulation has many advantages. If they are integrated in the whole product development cycle – from the conceptual design, through the process planning and die design, a complete *virtual design* environment can be created in a joint *Simulation and Knowledge Based System.*

On the basis of the described multi-stage forming process simulation, the following main conclusions may be drawn:

- Applying direct drawing and redrawing operations, four drawing stages are required. To produce rupture-free final product with this process plan an intermediate heat-treatment is also necessary.
- Applying an alternative process plan using reverse drawing, significant reduction in drawing steps can be achieved and the expensive intermediate annealing can also be eliminated.
- The suitability of the proposed process plans are clearly confirmed by the finite element simulation results.
- Besides the successful production plan, even the product quality can be improved by a more uniform thickness distribution as a result of the optimum drawing design.

This *Simulation and Knowledge Based* concept provides significant advantages both in the design and in the manufacturing phase. Applying the principles of Knowledge Based Expert Systems a fast engineering solution can be achieved, which combining with the recent achievements in FEM techniques provides theoretically more reliable results, i.e. more optimum design throughout the development cycle. This integrated approach will lead to significantly shorter lead times, better product quality and as a consequence more cost-effective design and production.

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