Recent development trends in sheet metal forming

Miklós Tisza

Department of Materials Processing Technologies,
University of Miskolc,
Miskolc-Egyetemváros, H-3515 Hungary
Fax: +36 46 561 504
E-mail: tisza.miklos@uni-miskolc.hu

Abstract: Sheet metal forming is one of the most important key technologies in manufacturing industry. It may be reasoned by several facts, among them the economy of the sheet-forming processes concerning the material and energy consumption, as well as the overall cost efficiency. To keep this key role of sheet metal forming in manufacturing industry, a continuous development is necessary concerning the materials, the development of new innovative forming processes, the tooling and manufacturing equipment. The ever-increasing requirements stated by the automotive industry may be regarded as one of the main driving forces behind sheet-metal-forming innovations. In this paper, some recent developments in sheet metal forming will be overviewed concerning the materials and process developments, as well as the application of various methods of Computer Aided Engineering (CAE).

Keywords: sheet metal forming; development trends; new materials; innovative new processes; CAE and FEM in SMF.

Reference to this paper should be made as follows: Tisza, M. (2013) 'Recent development trends in sheet metal forming', ***Int. J. Microstructure and*** *Materials Properties*, Vol. 8, Nos. 1/2, pp.125–140.

Biographical notes: Miklós Tisza obtained his MSc in Mechanical Engineering from the Technical University for Heavy Industry in 1972 and his PhD from the University of Miskolc in 1977. He has a DSc from the Hungarian Academy of Sciences (1994). He is a Fellow of the ASM International, Past President of IDDRG and member of Board of Directors of the European Scientific Association of Forming Materials (ESAFORM). He is the author of more than 20 books and has over 400 publications in leading international journals and conferences on various aspects of metal forming, computer-aided engineering and numerical modelling and simulation. Currently, he is the Head of the Department of Materials Processing Technologies at the University of Miskolc, Hungary.

This paper is a revised and expanded version of a paper entitled 'Recent development trends in sheet metal forming', presented at *8th ICIT&MPT Conference* at Ljubljana, 2–5 October, 2011.

1 Introduction

Sheet metal forming is one of the most important manufacturing processes. This is particularly valid for the automotive industry where sheet metal forming has an even more important key position. The automotive industry is the leading sector in many countries and the main driving force behind the sheet-metal-forming developments as well (Geiger, 2002).

The competition in car manufacturing is extremely strong leading to larger model variety and shorter model cycles. The increased competition also leads to a very intense development activity to increase productivity and to reduce costs.

Application of light-weight design principles is one of the most important trends to meet the above-mentioned requirements. Obviously, the new design concepts require new materials. The new materials often require new, innovative forming processes and new tooling concepts, as well.

The increased competition also requires to shorten the lead times from the concept to final realisation: to reduce the lead times, the application of various methods of Computer Aided Engineering (CAD/CAM/CAE and FEM techniques) are inevitable.

In this paper, the present state and some future outlook of these developments will be summarised concerning the materials, forming processes and tool design aspects.

2 Main development tendencies in sheet metal forming

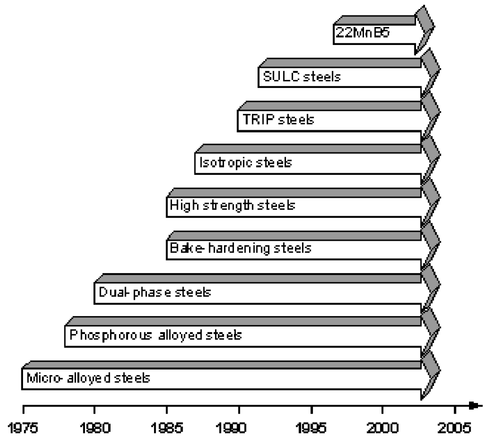
In this section, the main development tendencies will be overviewed in the fields of materials research, process development and tool design aspects.

2.1 Materials research and developments

Some decades ago, design engineers mainly focused their attention on structural and dimensional stability and durability. In recent years, the reduction of fuel consumption together with increasing comfort requirements led to the intensive development of innovative new materials. Enhanced stiffness together with weight reduction resulted in the development and wide application of various grades of high-strength steels. Nowadays, several micro-alloyed and phosphorous-alloyed steels both with and without bake-hardening are frequently used. An increasing use of Interstitial-Free (IF) steels, dual-phase and TRIP-steels, as well as the ultra low and super ultra low carbon steels can also be observed. These developments in steel materials are shown in Figure 1, concerning the last 30 years. From this figure, it can be seen that from the elaboration of various micro-alloyed steels in the mid-1970s of the last century, there is a continuous pressure on material development leading to the appearance of new advanced steel materials practically in each five year (Wagener, 1997).

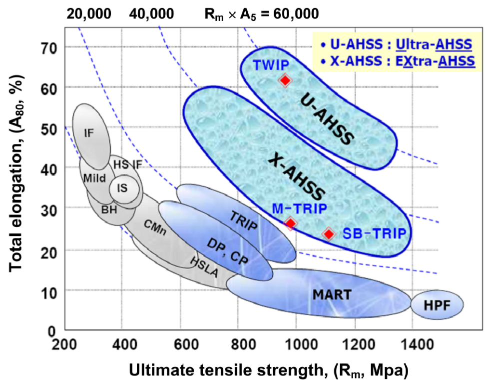
It is also well known that with the increase in strength properties a decrease in the ductility parameters can be observed, as it is illustrated in Figure 2; however, it is worth mentioning that for these new high-strength steels the increase in strength parameters is much more significant than the decrease in the ductility parameters (Chung and Kwon, 2008).

Figure 1 Time horizon of steel development in the automotive industry in the last 30 years



Source: Wagener (1997)

Figure 2 Tensile strength vs. total elongation for various steels (see online version for colours)



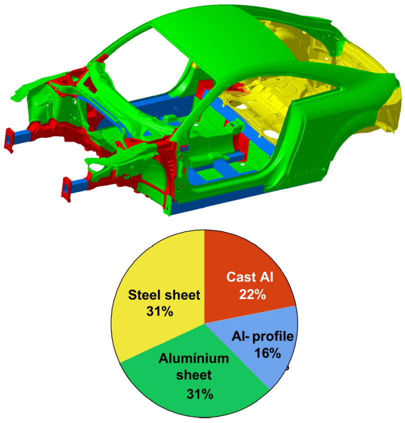
Source: Chung and Kwon (2008)

Because of the increasing demand for environment-friendly vehicles requiring reduced fuel consumption and weight, besides steel as structural material, aluminium alloys in automobiles are recently also widely used in car manufacturing for body-in-white production and their ratio will further increase as shown in Figure 3 (Waltl et al., 2007).

Many analyses have also shown that further significant weight reduction can be achieved in automobiles using fibre-reinforced composite materials. Carbon-fibre reinforced polyamide seems to be particularly suitable for this purpose: it satisfies the requirements of production in large series together with good mechanical strength and shape stability.

Concerning the materials, the sheet metal production development has to be also considered. Metal strips are usually manufactured by casting and rolling. Producing high-quality strips for further production, continuous slab casting has become already a widely used manufacturing process. Recently, thin slab casting and rolling has entered into a new development and application stage. By this method, thin strips of only few millimetres can be cast directly from the melt. In this way, thin strip can be produced more economically and even faster (Kopp, 2008). Later, it will be discussed, how new materials affect technological processes. However, new processes have also effect on the strip production. Tailored sheet products are good examples. Tailor-welded blanks are commonly used in automotive industry. On the basis of this demand, a new strip manufacturing process called flexible rolling emerged. This rolling technique is capable to provide strips with strictly controlled thickness changes that can be used for finished products with the right amount of material where it is needed to withstand varying loads (Kopp et al., 2003).

Figure 3 Multi-materials body concept in car manufacturing (see online version for colours)



Source: Waltl et al. (2007)

2.2 Innovative new forming processes

To elaborate new, innovative sheet-forming processes, the automotive industry always played a key role (Vöhringer, 1999), and on the other hand, automobile as a mass production would be unthinkable without forming technology: they have a mutually advantageous effect on each other resulting in a synergic interdisciplinarity of various sciences. Because of the limited extent of this paper, only a few, but representative examples will be shown from recent developments (Merklein et al., 2009).

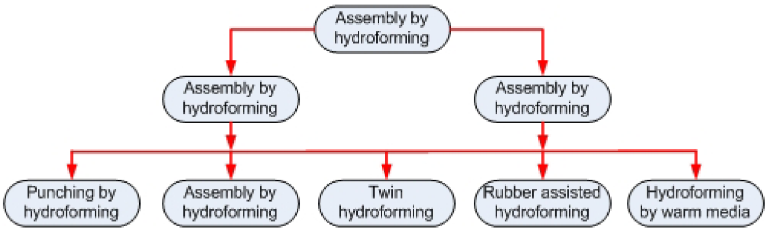
The rapidly emerging application of tailor-welded parts, which are already used in most modern vehicles, is one of the most characteristic examples in this respect (The Auto/Steel Partnership Tailored Welded Blank Project Team, 2001). Tailored blanks, where various sheets of different thickness or quality are welded together and formed subsequently to withstand various loads at different sections, are practically due to the developments in laser technology (Geiger and Merklein, 2004).

Nowadays, formability issues of tailor-welded blanks are one of the most important questions, to provide significant load-bearing parts with reduced weight without any decrease in shape or structural stability.

Recently, whole process chains were developed to further improve the suitability of light-weight structures. The whole process includes strip production with flexible rolling (the resulting sheet is often termed as tailor-rolled blank), and subsequent manufacturing of profile-shaped structural elements with profile bending forming processes. Light-weight structural elements produced by this process have less weight than any other comparable structures made from constant initial material thickness, and at the same time they have much better structural behaviour.

Among new, innovative forming processes hydroforming can be regarded as an outstanding one. Hydroforming is mainly used to produce hollow sheet or tube products – often with complicated geometry – to produce light-weight parts more economically. A classification system of hydroforming processes can be seen in Figure 4. The two basic groups are sheet hydroforming and tube or profile hydroforming. Various further subgroups can be created according to the applied processes as shown in Figure 4 (Lücke et al., 2001).

Figure 4 Classification of hydroforming processes (see online version for colours)



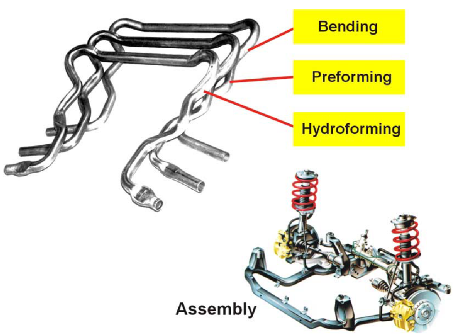
Source: Lücke et al. (2001)

In the automotive industry, tube hydroforming is already an industrially proven technique: various load-bearing components produced by this method can be already found in several cars. In Figure 5, an engine cradle can be seen as a typical example for tube hydroforming (Altan, 2000).

The development of hydroformed parts for large series production requires efficient methods both in the design and in the manufacturing phase to meet the requirements to produce high-quality parts in a cost-effective way. In most cases, the initial workpiece is a semi-finished product – usually a roll-formed tube made of hot- or cold-rolled, longitudinally welded strips.

Depending on the complexity of the component to be produced, hydroforming is usually applied together with additional preforming operations. These preforming operations often include prebending as also shown in Figure 5.

Figure 5 Engine cradle as a typical example for tube hydroforming (see online version for colours)

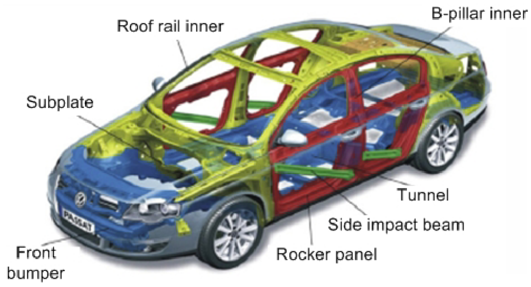


Source: Altan (2000)

Recently, hydroforming of double sheets has been developed and also seems to be a promising process to produce complicated sheet metal parts (Lang et al., 2004).

A further very promising field in process development is the emerging application of hot forming in producing automotive parts. It is also the result of the increasing demands to reduce the weight with increasing crash performance of car body components. These developments are good examples for the integrated development in materials and processes (Karbasian and Tekkaya, 2010). In Figure 6, typical hot formed parts are shown in a middle-cass car (Pepelnjak et al., 2009).

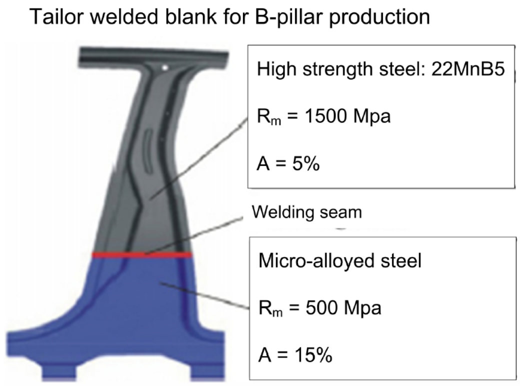
Figure 6 Hot stamped parts in a middle-class car (see online version for colours)



Source: Pepelnjak et al. (2009)

For hot forming operations, boron-alloyed steels like 22MnB5 are widely used, which are the so-called press hardening materials providing tensile strength up to 1500 MPa hardened in the tool. The hot forming process is performed at about 850°C, and requires special processes and tools. The B-pillar shown in Figure 7 is a good example for the application of hot forming (press hardening) process in the automotive part manufacturing (Tisza et al., 2008).

Figure 7 An example for the application of tailor-welded blanks (see online version for colours)



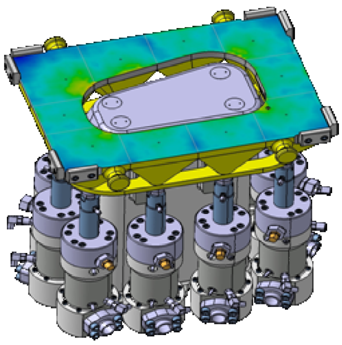
Source: Waltl et al. (2007)

2.3 Tool developments in the press shop

It is obvious that tool making has a vital role in the development in sheet metal forming. Since stamping tool manufacturing is one of the most cost expensive fields in the automotive industry, it is of utmost importance to reduce the time for tool design and manufacturing and to produce the 'right tools' at first. In this respect, the application of the various methods of Computer Aided Engineering including the computer-aided tool design and computer-controlled manufacturing, as well as the integrated product-, process- and die development with the application of numerical simulation, mainly the finite element modelling and simulation should be mentioned. Today, both the available computer technique and the various dedicated simulation codes, which were particularly developed for metal forming (and in many cases in close cooperation with the automotive industry), may be regarded as one of the most significant developments in the last 15–20 years. Because of these developments, tool making, which was for a long time rather an art of toolmaker masters, become a real science-based engineering discipline (Pepelnjak et al., 2009).

Among the many interesting tool developments, the application of local control of blankholder forces is a significant one. It is also a good example for the integrated process and tool development since the application of forming tools with segmented blankholder controls the forming process itself. This is important both in the deep-drawing of complicated parts and in the forming processes of tailor-welded blanks (Figure 8).

Figure 8 Segmented multi-cushion blankholder for in-process control of blankholder force (see online version for colours)



Source: Liewald and Schleich (2007)

3 Application of various methods of Computer Aided Engineering

During recent 10–15 years, the application of various methods of CAE and among them the Computer Aided Process Planning and Die Design evolved as one of the most important engineering tools in sheet metal forming, particularly in the automotive industry (Tekkaya, 2000; Sitaraman and Altan, 1991). This emerging role is strongly emphasised by the rapid development of Finite Element Analysis and Modelling, as well.

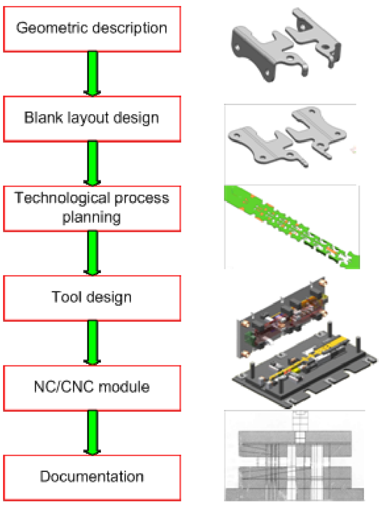
In this section, an integrated process simulation and die design system developed at the University of Miskolc, Department of Mechanical Engineering, will be analysed. The proposed integrated solutions have great practical importance in improving the global competitiveness of sheet metal forming in this very important segment of industry. The concept described in this paper may have specific value both for process planning and for die design engineers.

3.1 Knowledge-based engineering systems

As in many other metal-forming applications, process planning and die design for sheet forming can benefit from a combined application of knowledge-based systems and process modelling (Sitaraman and Altan, 1991). Recently, many companies are applying CAD/CAM techniques and knowledge-based expert systems to improve and partially automate die design and manufacturing function (Eshelby et al., 1986; Alberti et al., 1991).

Several program packages were elaborated for metal-forming processes at the University of Miskolc at the Department of Mechanical Engineering (Tisza, 1999). Among them, first a general CAD/CAM system for the process planning of sheet-forming processes performed in progressive dies should be mentioned (Tisza, 1990). The general scheme of this knowledge-based expert system can be seen in Figure 9.

Figure 9 Knowledge-based process planning and die design in CAD environment (see online version for colours)



Source: Tisza (1995)

In this system, the process planning and the die design functions are integrated into a knowledge-based expert system. It has a modular structure with well-defined tasks of each module and providing streamlined data and information flow between the various modules. 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.

3.2 Finite element modelling and simulation in metal forming

The forming simulation in sheet-metal-forming technology and its industrial applications have greatly impacted the automotive sheet metal product design, die developments, die construction and try-out, and production stamping in the past decade (Makinouchi, 1996). It led to significant progresses not only in fundamental understanding of sheet metal formability, forming mechanics, numerical methods, but also to the fruitful industrial applications in a wide range of industrial production (Altan et al., 1999).

The automotive die and stamping industry benefit most from the stamping simulations. The technology advancement speeds up the historical transition in automotive die development and stamping from a try-out-based workshop practice to a science-based, technology-driven engineering solution. The applications and benefits may be summarised as follows (Wang, 1999, 2002):

- stamping simulation is used as a Design for Manufacturability (DFM) tool to assess and validate the product styling surface designs to ensure a formable sheet product design
- it may be used as a die engineering tool in stamping die developments
- it may be used as a try-out tool to shorten production die try-out and thus to significantly reduce die cost and lead-time
- it may be used as a production tool to provide production stamping conditions (beads, lube, binder and press forces, etc.)
- it may be used as a problem-solving tool for production troubleshooting to reproduce manufacturing problems, and to provide solutions for process control improvements
- it may be used as a simulation-based manufacturing guide to use the simulation output to drive consistency among die engineering, die construction and production stamping
- finally, the stamping simulation may be used as a learning tool to explore and gain new knowledge and application guidance for new forming techniques and new materials.

In today's die and stamping industry, the simulation for virtual validations of die developments before production trials is a critical business for lead-time reduction, cost reduction and quality improvements (Altan and Vasquez, 2000). The global competitions drive higher-quality requirements, lower cost and shorter lead-time. The competitions also drive the industry to use more new designs, new materials and new forming processes. These trends in automotive stamping can be summarised as follows (Wang, 2005a).

- increasing part size and shape complexity such as whole body side panels and multiple attached parts formed in one die to improve productivity and reduce die cost
- increasing material diversity to meet different needs such as using light-weight material (aluminium) for fuel economy, using stronger material for safety (dual-phase steel, TRIP steel and ultra-high strength steels), using laminated metal–plastic–metal sheets for noise and vibration reduction and using tailor-welded blank to reduce the number of parts for better structure integrity

- increasing use of unconventional forming processes such as hydroforming for extra deep drawn panels, superplastic forming for complicated parts and forming with intermediate annealing for materials very difficult to form.

All these new trends create new challenges for stamping simulation from fundamental research to software development and to production applications.

One of the main drawbacks in industrial practice hindering the even more wide application of simulation techniques is that the output results of simulation packages usually cannot be used directly and easily for computer-aided die design (Wang, 2005b). Obviously, there are tremendous efforts to successfully link CAD and FEM systems; however, still there are a lot to do in this field (Andersson, 2001). This solution requires a fully integrated approach of computer-aided product design, process planning and die design, as well as the finite element simulation of the forming processes. It means that simulation tools should be efficiently used throughout the whole product development cycle (Andersson, 2004).

3.3 Process planning and die design in conventional CAD environment

Stamping industry applies CAD techniques both in the process planning and in the die design already for many years. However, in a 'traditional' CAD environment, these are practically *stand-alone* solutions, i.e., for example a knowledge-based process planning solution is applied for the determination of the necessary types of forming processes, even in some cases, the forming sequences can be determined in this way together with the appropriate process parameters, too. After determining the process sequences and process parameters, the forming dies are designed using sophisticated CAD systems; however, still we do not have any evidence whether the designed tools will provide the components with the prescribed properties. Therefore, before it goes to the production line, usually a time- and cost-consuming try-out phase follows.

If the try-out is successful, i.e., the die produces parts with no stamping defects, it will be sent to the stamping plant for production. On the other hand, if splitting or wrinkling occur during the try-out, the die set needs to be reworked. It means that we have to return first to rework the die construction by changing the critical die parameters (e.g., die radii, drawing gap, etc.). If it does not solve the problem, a new die design, or a new process planning is required. In some cases, we have to go back even to the product design stage to modify the product parameters. The more we go back the higher the development and design costs are. Occasionally, the die set is scraped and a perfectly new product-, process- and die design is needed. As a result, die manufacturing time is increased as well as the cost of die making.

3.4 Simulation-based process planning and die design

Because of the global competition – and this is particularly valid for the automotive industry – there is an overall demand to improve the efficiency in both the process planning and in the die design phase, as well as to reduce the time and product development costs and to shorten the lead times. It requires the efficient use of simulation techniques from the earliest stage of product development, to give feedback from each step to make the necessary corrections and improvement when it takes the least cost (Tisza, 2005a; Tang et al., 2005).

With this approach, stamping defects may be minimised and even eliminated before the real die construction stage. If any correction or redesign is needed, it can be done immediately, with a very short feedback time, thus it leads to a much smoother die try-out if necessary at all and to significantly shorter lead times with less development costs (Ramadoss and Rajadurai, 2011).

However, even with this approach, there are some further shortfalls in the die design process, since most of the simulation programs do not provide die construction in sufficient details, which can be easily used in most CAD systems to complete the die design task. This shortage may be overcome by integrating the CAD and FEM systems through a special interface module, which can provide a smooth, continuous and reliable data exchange between the two important parts of design process. The solution for this shortage is the application of an integrated simulation and knowledge-based approach, which will be described in detail in the next section (Tisza, 2004).

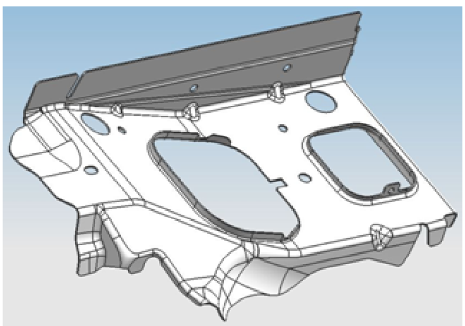
3.5 Simulation and knowledge-based systems: an integrated approach

This solution will be described through the example of an automotive sheet metal component using the Unigraphics NX as the CAD system and the AutoForm® as the FEM package; however, the principles applied here can be adopted to other programs as well (Tisza, 2005b).

The selection of these two program packages can be explained by several reasons. On the one hand, both the Unigraphics and the AutoForm are among the most widely applied packages in the automotive industry. On the other hand, these two systems are among the first to offer a special interface module to enhance the information and data exchange between CAD modelling and FEM simulations in both directions making possible the most efficient integration during the whole product development cycle. In the following, this solution will be described in detail following the road map of this simulation-guided process planning and die design procedure.

The CAD model of the component created by the product design engineer is shown in Figure 10. As it often happens in the automotive part production, the component has a symmetric counterpart (the so-called left- and right-handed or double attached parts).

Figure 10 CAD model of the component to be manufactured (see online version for colours)



The part model is created in Unigraphics as a solid model. However, FEM systems dedicated for sheet metal forming usually require surface models. Therefore, before exporting the part model, a surface model should be created. This function is well supported in most CAD systems. Depending on the simulation requirements, even we can decide which surface (top, middle or bottom) will be exported into the surface model.

In most cases, process planning engineers would like to know right at the beginning whether the component can be manufactured with the planned formability operations. Therefore, after importing the surface model of the component with the AutoForm input generator, first a fast feasibility study should be performed.

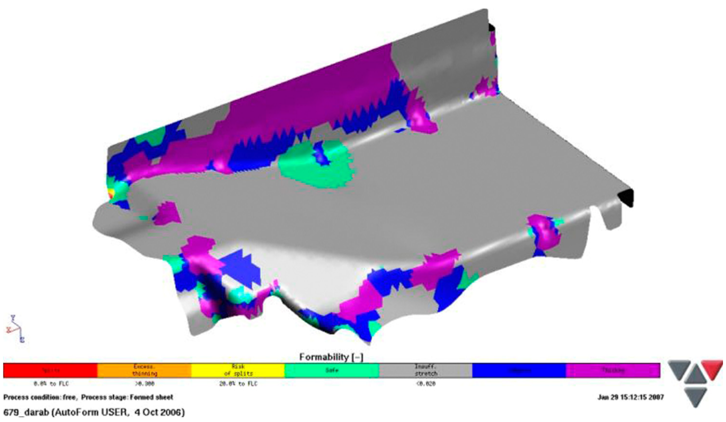
The AutoForm has an extremely well-suited module for this purpose: this is the so-called One-Step simulation module, where the formability analysis can be done even if we do not have any or just very few information on the forming tools. Using this One-Step simulation procedure, a quick decision can be made if any modification of the part is required.

Besides the part formability validation in this very early stage of product development, further important possibilities are also offered in this module including the analysis of slight part modifications, studying alternative material types and grade, or various thicknesses, material cost estimation and optimisation.

If this feasibility study is successful (see, for example, for this component in Figure 11), the work of process planning engineer can be efficiently supported by determining the optimum blank shape and sizes.

The optimum blank determination is particularly important when we have such a complicated part, where besides the expected intricate contour line, we have to consider the joined shape of left- and right-handed, double attached parts, as well. The precise determination of optimum blank is important from other points of view as well.

Figure 11 One-step formability study of the part (see online version for colours)



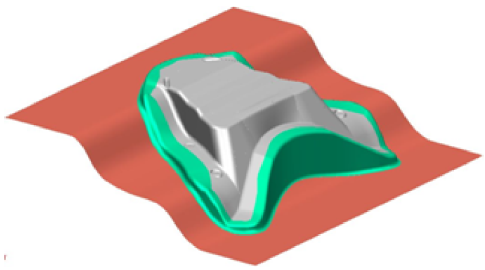
As it can be seen from the CAD model of the part (Figure 10), a trimming operation is practically impossible when the part is already formed owing to its complex 3D part boundary line. Therefore, we have to apply a blank geometry, which does not need any trimming operation in spite of the complicated 3D forming operations, i.e., when the forming is finished, we have the required part boundary line within the prescribed tolerances. Furthermore, this optimum blank is also necessary for the determination of material utilisation, which can be done in the Nesting and Blank-layout module. This is also important starting information for the detailed, incremental forming simulation.

Even if the One-Step simulation resulted in good formability, the final decision on the whole process realisation can be made only after performing a detailed incremental modelling particularly concerning the critical forming steps. For this detailed simulation, we need already very detailed knowledge on the tools and process parameters.

The active surfaces of the forming tools can be derived from the imported surface model of the component to be produced utilising the many useful possibilities offered by the Die-Designer module to create the binder and addendum surfaces, as well as the so-called reference surface, which can be used to quickly derive the punch and die surfaces, as well (Figures 12 and 13).

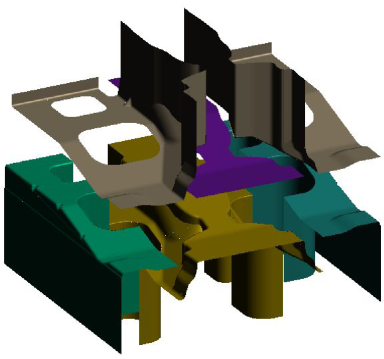
Figure 12 The optimum blank trimmed for the final shape (see online version for colours)

Figure 13 Reference surface to derive the tool surfaces (see online version for colours)



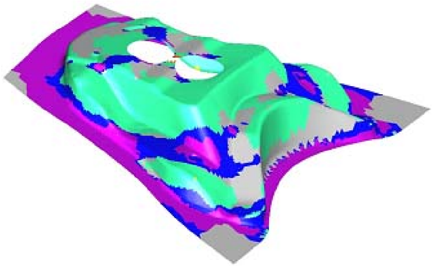
Applying this simulation tool set-up, incremental simulation can be performed with various process parameters, and depending on the simulation results, several modifications on the tool parameters can also be made. The simulation tool set-up determined with the Die-Designer module for this component can be seen in Figure 14 after some minor modifications.

Figure 14 Simulation tool set-up for the incremental process simulation (see online version for colours)



In some cases – as it happened with this part, too – we could not achieve a perfect, defect-less part owing to the excessive stretching at the die radius shown. This problem was solved by applying the so-called free cut-off lines in the middle of the double attached part, which is in the scrap region after separating the left and right parts. This modification resulted in a defect-free component as shown in Figure 15.

Figure 15 Defect-free double attached part with cut-off lines (see online version for colours)



When these active tool elements are derived, the complete tool assembly can be created using the design capabilities of the Unigraphics CAD system.

4 Conclusions

In this paper, recent development trends in sheet metal forming were overviewed concerning the applied materials, the forming processes, as well as the tooling concepts and die design practice.

Concerning the material research and development, the increasing application of high-strength steels as well as the so-called multi-material concept was emphasised. Among the many new, innovative process developments, some selected examples were shown including the application of tailor-welded blanks, laser technology and hydrofoming processes.

A significant part of this paper deals with the various CAE methods applied in sheet metal forming. It was clearly shown that the CAE has a vital and central role in the whole product development cycle. The application of various methods and techniques of CAE activities resulted in significant developments: the formerly trial-and-error-based workshop practice has been continuously transformed into a science-based and technology-driven engineering solution.

In this paper, an integrated approach for the application of knowledge-based systems and finite element simulation is introduced. Applying this knowledge- and simulation-based concept for the whole product development cycle – from the conceptual design through the process planning and die design as an integrated CAE tool – provides significant advantages both in the design and in the manufacturing phase. Sheet-metal-forming simulation results today are already reliable and accurate enough that even try-out tools and the time-consuming try-out processes may be eliminated or at least significantly reduced. Thus, the integrated solution described in this paper results in significantly shorter lead times, better product quality and as a consequence more cost-effective design and production.

Acknowledgements

This research work was jointly financed by the EUREKA_HU_ISMFP_ME and the TÁMOP-4.2.2.A-11/1/KONV-2012-0029 projects. Both financial supports are gratefully acknowledged.

References

Alberti, N., Cannizaro, L. and Micari, F. (1991) 'Knowledge based systems and FE simulations in metal forming processes', *Annals of CIRP*, Vol. 40, No. 1, pp.295–298.

Altan, T. (2000) 'Tube hydroforming: state of the art and future trends', *Journ. of Mat. Proc. Techn.*, Vol. 98, No. 1, pp.25–33.

Altan, T. and Vasquez, V. (2000) 'New concepts in die design – physical and computer modelling', *J. of Mat. Proc. Techn.*, Vol. 98, No. 2, pp.212–223.

Altan, T., Thomas, W., Vazques, V. and Koc, M. (1999) 'Simulation of metal forming processes', *6th ICTP Conf.*, 19–24 September, Nuremberg, Vol. 1, p.23.

Andersson, A. (2001) 'Information exchange within tool design and sheet metal forming', *J. of Engineering Design*, Vol. 12, No. 4, pp.283–291.

Andersson, A. (2004) 'Comparison of sheet metal forming simulation and try-out tools in design of forming tools', *J. of Engineering Design*, Vol. 15, No. 6, pp.551–561.

Chung, J.Y. and Kwon, O. (2008) *Development of High Performance Auto Steels*, ICTP, 7–11 September, Gyeongju-Korea, pp.3–6.

Eshelby, L., Barash, M. and Johnson, W. (1988) 'A rule based modelling for planning axisymmetric deep-drawing', *Int. J. of Mech. Sciences*, Vol. 14, No. 1, pp.1–113.

Geiger, M. (2002) 'Manufacturing science – driving force for innovation', *Adv. Technology of Plasticity*, Vol. 1, No. 1, pp.17–30.

Geiger, M. and Merklein, M. (2004) 'Laser and forming technology', *Journ. of Mat. Proc. Techn.*, Vol. 151, pp.3–11.

Karbasian, H. and Tekkaya, A.E. (2010) 'A review on hot forming', *Journal of Materials Processing Technology*, Vol. 210, pp.2103–2118.

Kopp, R. (2008) *Innovations in Metal Forming in the World*, ICTP 2008, 7–11 September, Gyeongju-Korea, pp.7–24.

Kopp, R., Kuhlen, T. and Kneppe, G. (2003) 'Virtual reality in metal forming', *3rd European Rolling Conference*, 16–20 June, Prague, Strip rolling, pp.210–215.

Lang, L.H., Wang, Z.R. and Kang, D.C. (2004) 'Hydroforming highlights: sheet and tube hydroforming', *Journ. Mat. Proc. Techn.*, Vol. 151, Nos. 1–3, pp.165–177.

Liewald, M. and Schleich, R. (2007) 'Robust processes in sheet metal forming', *Proc. of IDDRG'2007*, 21–23 May, Győr, Hungary, pp.13–22.

Lücke, H.U., Hartl, Ch. and Abbey, T. (2001) 'Hydroforming', *Journal of Materials Processing Technology*, Vol. 115, No. 1, pp.87–91.

Makinouchi, A. (1996) 'Sheet metal forming simulation', *J. Materials Processing Technology*, Vol. 60, Nos. 1–4, pp.19–26.

Merklein, M., Geiger, M., Staud, D. and Vogt, U. (2009) 'Tailored heat treated blanks applied on car body parts under quasi-series conditions', *International Journal of Microstructure and Materials Properties*, Vol. 4, Nos. 5–6, pp.525–533.

Pepelnjak, T., Kuzman, K., Klinc, M. and Gantar, G. (2009) 'Mastering the stamping of high strength steels in Slovene tool making industry', *International Journal of Microstructure and Materials Properties*, Vol. 4, Nos. 5–6, pp.562–575.

Ramadoss, R. and Rajadurai, A. (2011) 'Finite element simulation of forming limit diagram for AISI 316LN-Austenitic stainless steel', *International Journal of Microstructure and Materials Properties*, Vol. 6, No. 6, pp.507–525.

Sitaraman, S.K. and Altan, T. (1991) 'A knowledge based system for process sequence design in sheet metal forming', *J. of Mat. Proc. Techn.*, Vol. 25, No. 3, pp.247–271.

Tang, A., Lee, W.C., St. Pierre, S., He, J., Liu, K. and Chen, C.C. (2005) 'CAE based die face engineering development', *NumiSheet 2005 Conf.*, 19–24 September, Detroit, pp.50–60.

Tekkaya, A.E. (2000) 'State of the art of simulation in sheet metal forming', *J. Mat. Proc. Techn.*, Vol. 103, No. 1, pp.14–22.

The Auto/Steel Partnership Tailored Welded Blank Project Team (2001) *Tailor Welded Blank: Applications and Manufacturing*, Southfield, Michigan, June, pp.1–91.

Tisza, M. (1990) 'A complete CAD/CAM system for metal forming', *2nd Int. Conf. on CAD/CAM and Robotics*, 22–26 August, London, pp.110–117.

Tisza, M. (1995) 'Expert system for sheet metal forming', *J. of Mat. Proc. Techn.*, Vol. 53, Nos. 1–2, pp.423–432.

Tisza, M. (1999) 'Numerical modelling and knowledge based systems in metal forming', *ICTP Conf.*, Advanced Technology of Plasticity, 19–24 September 1999, Nuremberg, Vol. 1, pp.145–154.

Tisza, M. (2004) 'Numerical modelling and simulation in sheet metal forming', *Journal of Materials Processing Technology*, Vol. 151, Nos. 1–3, pp.58–62.

Tisza, M. (2005a) 'Numerical modelling and simulation: academic and industrial perspectives', *Materials Science Forum*, Vols. 473–474, No. 1, pp.407–414.

Tisza, M. (2005b) 'Rapid parametric process design using FEM', *Advanced Materials Research*, Vols. 6–8, No. 1, pp.235–240.

Tisza, M., Lukacs, Zs. and Gal, G. (2008) 'Numerical modelling of hot forming processes', *International Journal of Microstructure and Materials Properties*, Vol. 3, No. 1, pp.21–34.

Vöhringer, K-D. (1999) 'Metal forming – a key technology for automobile production', *Adv. Techn.*, Vol. 1, pp.3–12.

Wagener, H.W. (1997) 'New developments in sheet metal forming: sheet materials, tools and machinery', *Journ. Mat. Proc. Techn.*, Vol. 72, No. 3, pp.342–357.

Waltl, H., Vette, W. and Griesbach, B. (2007) *Tool-Making for Future Car Bodies*, IDDRG'2007, 21–23 May, Győr, Hungary, pp.31–44.

Wang, C.T. (1999) 'Advanced stamping simulation technology – state of business and industrial prospect', *Numisheet Conf.*, 13–17 September, Besancon, pp.250–256.

Wang, C.T. (2002) 'An industrial outlook for springback predictability', *NumiSheet 2002*, 21–25 October, Jeju Island, Korea, pp.597–604.

Wang, C.T. (2005a) 'Evolutions of advanced stamping CAE', *NumiSheet 2005 Conf.*, 19–24 September, Detroit, pp.78–82.

Wang, C.T. (2005b) 'A road map for simulation-guided die try-out and stamping process control', *NumiSheet 2005 Conf.*, 19–24 September, Detroit, pp.66–69.