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COMPUTER AIDED SHEET METAL FORMING PROCESS DESIGN

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Abstract

A system for the computer aided design of sheet metal forming is described. This system was combined with the FEM and theoretical method of determination of a forming limit stress diagram (FLSD). A theoretical method was also developed for determining the FLSD, which is based on the perturbation theory. The perturbation analysis is based on the introduction of a disturbance added to homogeneous solution satisfying the set of governing differential equations of the problem. The finite element technique is used to compute springback compensation in complex parts. This compensation can be computed from the deformed shape of the blank by applying the press and frictional forces to the deformed sheet with equal magnitudes but opposite signs; the additional deformation is the amount of springback. This system assures high quality of the products for both simple and complex press forming operations, including deep drawing and stamped part trimming. An original method of controlling and diagnosing press forming processes on the basis of measurements of the magnetic field around the stamped part has been developed. The method is based on the magnetic effect which consists in the generation of a magnetic field by a ferromagnetic body subjected to a mechanical load. Using the system it is possible to design with high precision the sheet metal forming processes without expensive and time consuming trial and error techniques.

Key words: deep drawing, press tools design, automatic diagnosis, springback, finite element method

1. INTRODUCTION

Metal forming processes such as sheet metal forming, punching, trimming and cutting are becoming more and more important, and the requirements set to these processes are still increasing as regards complex shape, close tolerances, no defects, material properties, minimised scrap material and long tool life. An extensive effort has been devoted to the development of analytical tools and mathematical models capable of simulating sheet metal forming processes. The purpose of such effort is to provide the design engineer with analytical tools for testing design at the computer terminal so that the expensive trial and error process with the real tools may be reduced or eliminated.

A system for the computer aided design of sheet metal forming has been based on the finite element method supplemented with a sheet metal drawability criterion and a computing algorithm which minimizes the shape error caused by stamped part springback. The computer aided design system ensures that the parts display no material instability and high dimensional shape accuracy.

The industrial manufacturing technology of most sheet metal parts comprises deep drawing and trimming. The mentioned operations induce stresses in the sheet. As a result of the stress relaxation after these operations, the deformed shape is different from the desired one (springback). In order to respect the design tolerances, much effort has been spent to investigate efficient methods to reduce

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springback (Ayres, 1984; Liu, 1988; Stevenson, 1993; Wenner, 1983). In these methods a reduction in springback is obtained by maintaining strong tensile forces in the deformed material, and by using multi-step process, and variations of the binder force during the forming process. Wenner (1983) has shown that tensile stress in superposition with bending stress reduces springback during the bending of elastoplastic materials. Webb and Hardt (1991) analysed part shape errors caused by springback in order to correct the shape of the tools. They modified the stamp and the matching die in a closed computing algorithm, which was run until the geometrical deviations were corrected. A similar approach was used by Karafillis et al. (1996) in a reversed springback method. Kawka et al. (1998) showed how difficult the simulation of springback and trimming operations may be.

An analytical method (Zimniak, 2005) for computing springback compensation after deep drawing and trimming is used to produce parts of a particular shape. The proposed compensation method is based on finite element technique and closed loop algorithm, which acted to correct the part shape error.

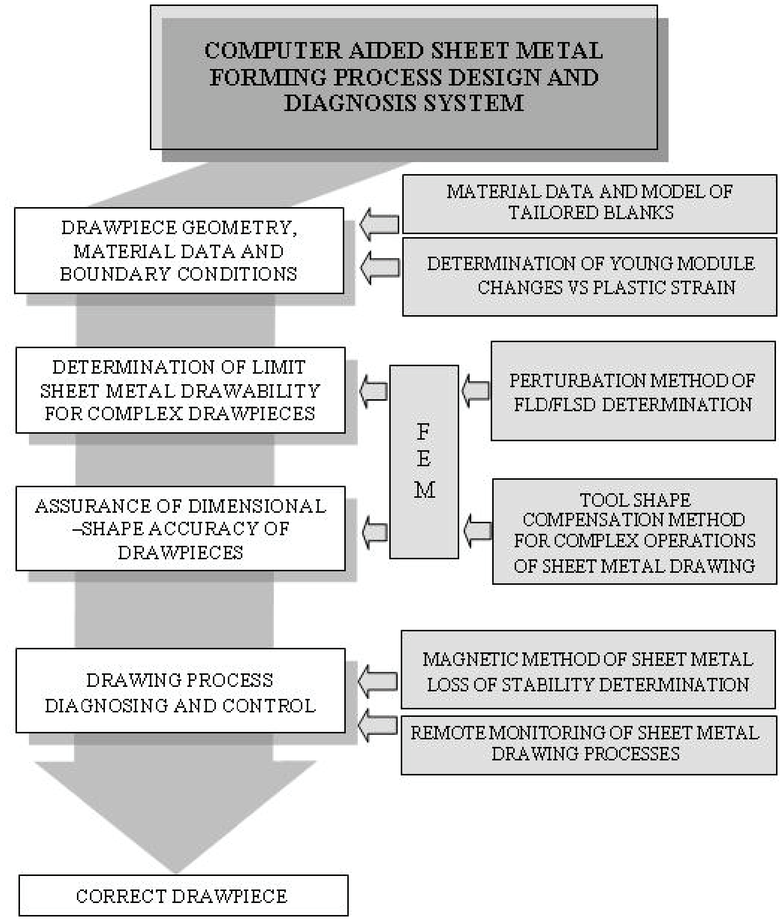

Fig. 1. Chart of the computer aided design and diagnosis system for sheet metal forming

Combining this system in a computer aided process design makes it possible to design processes without expensive and time consuming trail and error techniques.

2. DESCRIPTION OF A COMPUTER AIDED DESIGN SYSTEM FOR SHEET METAL DEEP DRAWING

This paper deals with problems relating to a computer aided design system for sheet metal deep drawing . The system is based on the finite element method supplemented with a sheet metal drawability criterion and a computing algorithm which minimizes shape error caused by springback. The computer aided design system ensures that stamped parts without material instability and with high dimensional shape accuracy are obtained. A new method of diagnosing sheet metal forming process for part manufacturing has been developed. The chart of the computer aided process design and diagnosis system is shown in figure 1.

The computer aided design system is a software package running on workstations with considerable computing power. It enables the analysis of design correctness for any complex three dimensional stamped part. It is based on the finite element method with a drawability assessment system based on forming limit stress diagrams (FLSD) incorporated in it. If a risk of exceeding limit stress is identified, the process conditions and the kind of sheet material can be changed or the part shape can be modified and an analysis of the process can performed again. Or leaving the shaping conditions unchanged, one can determine the maximum part depth. The press forming tool shape compensation model makes it possible to compensate springback in complex sheet metal forming operations, including deep drawing, trimming and die shearing. Thanks to the use for theoretical FLSDs, a wide range of industrial press forming processes characterized by a highly nonlinear deformation path can be analysed. The modified perturbation method, employing a complex material work hardening curve and a plasticity function, has been applied to determine FLSDs. It differs from the commonly used theoretical limit strain method – the Marciniak-

Kuczyński theory – in the fact that no initial material inhomogeneity, a parameter difficult to determine in practice, is assumed. Instead, a small perturbation is introduced into the homogenous solution of the problem.

An original method of springback compensation for complex sheet metal forming operations, including deep drawing and part trimming and die shearing, has been developed. This combination of sheet metal forming operations is very common in industry. The method of press forming tool shape compensation consists in creating virtual tools on the basis of typical results of the computer simulation of the press forming process. In this way, by taking into account the shape error caused by part material springback, the proper shape of the tools can be determined.

High quality of stamped parts must be continuously assured. The function of the press forming process control and diagnosis system is to provide complex information about the quality of the parts. An original method of controlling and diagnosing the press forming process, based on measurements of the magnetic field is proposed. The method exploits the magnetomechanical effect which consists in the generation of a magnetic field by a ferromagnetic body subjected to a mechanical load.

The computer aided design system can handle tailored blanks. In order to produce them, different kinds of sheets with geometrical and physical features must be joined together by laser welding. The magnetic measurement method is used to determine the material model of the laser welded sheets.

The computer aided design system allows to properly analyse a wide range of press forming processes. It has proved to be effective for different materials used in press forming, such as deep drawing steel, aluminium, brass, stainless steel and titanium steel. The experimental verification of the whole system has proved useful for sheet metal forming design.

3. ESTIMATION OF THE SHEET METAL FORMABILITY

The numerical tools must be able to predict the onset of a plastic instability, for instance by using a criterion for the prediction of localised necking. A forming limit stress diagram (FLSD) is implemented in the finite element simulations, and makes possible to determine accurately the onset and propagation of localised necking. The FLSD diagram is independent of the deformation history (Gronostajski, 1984) and more useful than the classical forming limit diagram (FLD) (Gronostajski & Zimniak, 1996). Calculation of FLSD in the present work was determined by a perturbation analysis (Dudzinski & Molinari, 1991) of deformation. The analysis combines the main advantage of both the theory of Marciniak and Kuczyński (1967) and the bifurcation theory. Other advantage is that quite general material behaviour can be accounted for.

The main elements of the developed perturbation analysis are presented below. The sheet is assumed to be initially homogeneous. At any stage of the postulated homogeneous deformation process, a perturbation is superimposed to the basic homogeneous flow. The flow instability or stability is characterised by the fact that the perturbation is increasing or decreasing. The localized necking phenomenon is a local instability problem associated with local equilibrium equations and constitutive equations of the material for a given state of strain and stress. A biaxial deformation mode described by the strain rates D^0_{xx} and D^0_{yy}, is imposed at the remote boundaries of a sheet (reference system x-y, see figure 2).

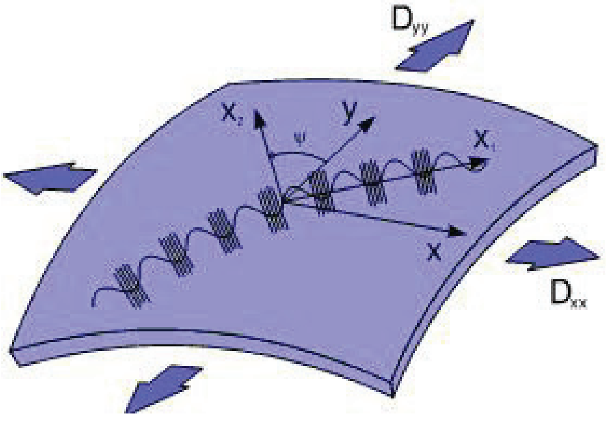

Fig. 2. The reference systems used in the perturbation analysis

The straining path is linear and defined by the ratio:

$$\rho = \frac{D^o_{yy}}{D^o_{xx}} = const. \tag{1}$$

Barlat yield function for planar anisotropy of sheet metals (Barlat et al., 1991) is introduced into the perturbation theory. The yield function is expressed as:

$$\Phi\left(\sigma_{xx},\sigma_{yy},\sigma_{xy},\sigma_{yx}\right) = a\left|k_1+k_2\right|^m + a\left|k_1-k_2\right|^m + \left(2-a\right)\left|2k_2\right|^m \tag{2}$$

$$k_1 = \frac{\sigma_{xx} + h\sigma_{yy}}{2} \tag{3}$$

$$k_2 = \sqrt{\left(\frac{\sigma_{xx} - h\sigma_{yy}}{2}\right)^2 + p^2\sigma_{xy}^2 + p^2\sigma_{yx}^2} \tag{4}$$

$$h = \sqrt{\frac{R_0\left(1+R_{90}\right)}{\left(1+R_0\right)R_{90}}} \tag{5}$$

$$a = 2 - \sqrt{\frac{R_0R_{90}}{\left(1+R_0\right)\left(1+R_{90}\right)}} \tag{6}$$

$$p = \frac{\sigma_p}{\sigma_b} \tag{7}$$

where: σ_p is the yield stress in balanced biaxial tension and σ_b is the major yield stress in plane-strain tension, m is a material parameter. R_0 and R_{90} denote the Lankford coefficients measured in the rolling direction and perpendicular to the rolling direction, respectively.

In this paper a new constitutive law is proposed (Gronostajski, 1997) and used in the perturbation analysis:

$$\bar{\sigma} = K(\bar{\varepsilon} + \varepsilon_o)^n \exp(n_1\bar{\varepsilon})\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_o}\right)^{\left(a_1\bar{\varepsilon} + a_2\bar{\varepsilon}^2\right)} \tag{8}$$

Knowing the hardening low and the yield surface, a homogeneous solution can be obtained in the rotated reference system x_1-x_2 at any moment of the deformation. This solution is denoted by the subscript:

$$P^{\mathrm{o}} = \left(D_{11}^{\mathrm{o}}, D_{22}^{\mathrm{o}}, D_{33}^{\mathrm{o}}, D_{12}^{\mathrm{o}}, \sigma_{11}^{\mathrm{o}}, \sigma_{22}^{\mathrm{o}}, \sigma_{12}^{\mathrm{o}}, \bar{\sigma}^{\mathrm{o}}, \dot{\bar{\varepsilon}}^{\mathrm{o}}\right) \tag{9}$$

The stability of this solution is then analysed by superimposing a small perturbation $\delta P = \left(\delta D_{11}, \delta D_{22}, \ldots, \delta\dot{\bar{\varepsilon}}\right)$ which is assumed to have the following form:

$$\delta P = \delta P^o \exp[\eta(t - t_0)]\exp(i\xi x_1) \tag{10}$$

The spatial modulation is periodic and defined by the wave number ζ. The factor η characterizes the rate of growth of the perturbation. The perturbed solution is

$$P = P^{\mathrm{o}} + \delta P \tag{11}$$

For the above perturbation problem equations can be linearized and written in the following form:

$$S\delta P^o = 0 \tag{12}$$

A non-zero solution exists if the determination of the linear equation system (12) is null. In this way, a cubic equation can be obtained for parameter:

$$\hat{\eta} = \frac{\eta}{\dot{\bar{\varepsilon}}^o} \tag{13}$$

The perturbation theory predicts an effective instability when one of the roots of the cubic equation has a real and large enough value:

$$\mathrm{Re}(\hat{\eta}) > e \tag{14}$$

where e is the intensity of the instability.

When the above condition is attained, a necking process starts in a band inclined at the given angle ψ (angle of the rotated reference system). The criterion from the perturbation analysis checks the deformation state (stress, strain, strain rate, strain ratio) and calculates the FLDs and FLSDs from the constitutive relationship, the strain ratio and strain rate. The modification of the perturbation theory by new stress-strain relation and

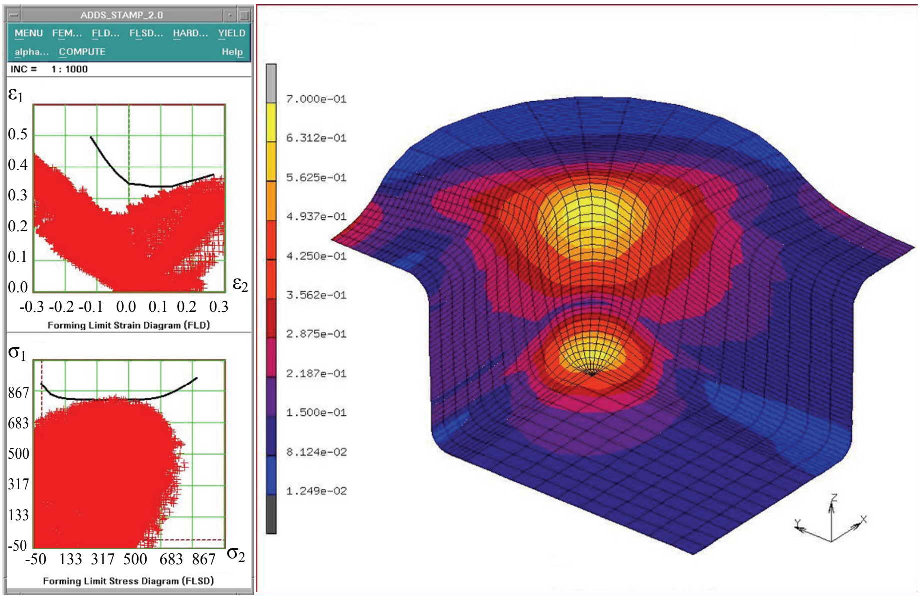

Fig. 3. The simulation of deep drawing of a square cup process and strain distribution with respect to FLD and FLSD for SOLDUR 340 steel

six-component Barlat yield surface gives a good prediction of the onset of necking for numeric simulation of a deep drawing operation.

Experimental verification of the prediction of localised necking is performed for deep drawing of a square cup.

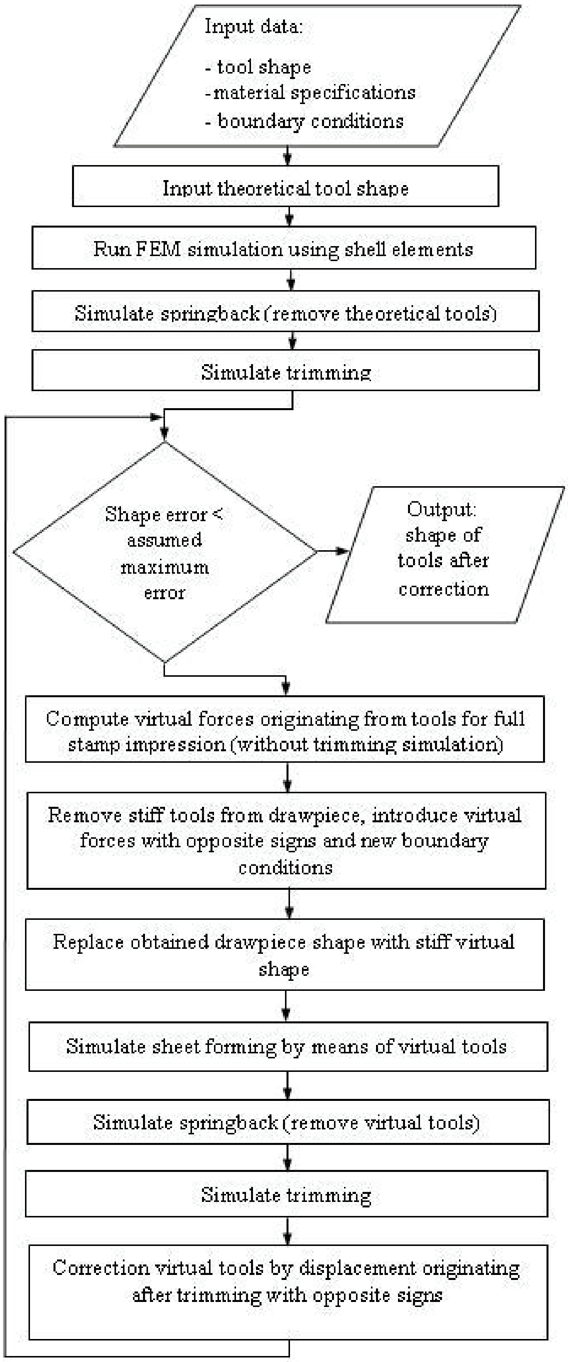

Fig. 4. Algorithm of the tool shape compensation method

The FEM simulations were performed on the ¼ symmetric area for SOLDUR 340 steel. The rigid die is a flat surface with a square hole (200 mm by 150 mm), rounded at the edges with a radius 20 mm. The rigid square punch is 197 mm by 147 mm and is rounded at the edges with 6 mm radius. Friction between the blank and rigid surfaces was modelled using Coulomb law. A blankholding force of 29.9 kN and a friction coefficient of 0.132 were used. Figure 3 shows the simulation of deep drawing of a square cup process and strain distribution with respect to FLD and FLSD for SOLDUR 340 steel.

The difference between the experimental and predicted necking major strain levels (ε_1= 0.37 and 0.35 respectively) is very small.

4. METHODS OF ENSURING DIMENSIONAL ACCURACY OF STAMPED PARTS

The FEM-based algorithm was used to compensate error due to springback by modifying the tool shape. The proposed method consists in the creation of virtual tools based on typical results of computer simulations of the forming process in order to determine tool shape compensation. The algorithm is shown in figure 4.

In the shape-dimension compensation method, sheet forming by means of rigid tools is simulated (for a theoretical tool shape) and after the last simulation step (full stamp impression) the tools are removed and the virtual forces (having the same values but opposite signs) originating from them are applied at the part's nodes, which were in contact with the tools. Then the part loaded with the virtual forces is simulated and the corrected shapes of the tools (virtual tools) are obtained. In the following step the virtual tools are replaced by the rigid tools and sheet forming by means of the latter tools is simulated. Then deviations from the ideal product are determined and if the part does not meet the shape error requirements, the entire procedure is repeated from the beginning until a part shape with the admissible error is obtained.

When multi-step stamping processes (including springback and trimming operations) are analysed, simulation of trimming should be included as is shown in figure 4. Calculations of the trimming consist of three independent steps described in figure 5.

First, the group of elements is removed from the mesh. Next, non equilibrated forces are calculated based on the element stress field for all nodes on the trimming line. Then, for each node on a trimming line an additional force boundary condition is imposed (non balanced forces with opposite signs), and calculations are continued until all nodal forces on the trimming line vanish.

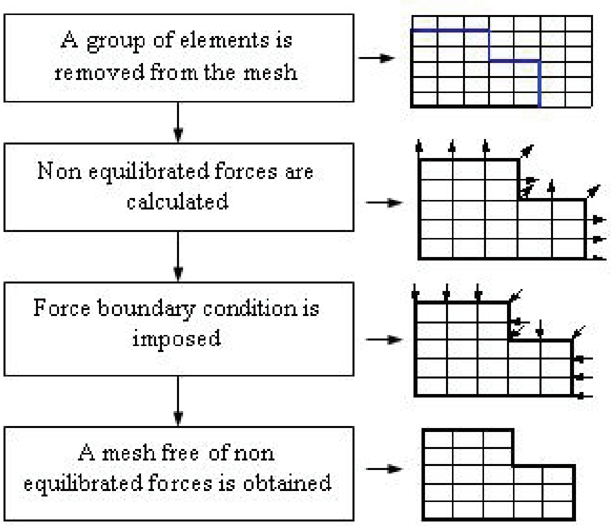

Fig. 5. Simulation of the trimming process

The tool shape compensation method presented earlier was applied to FEM modeling of the forming process of a part with complex geometrical shape. The method minimizing springback errors was used in order to determine corrected tools shape and for the comparison of theoretical and experimental results. Whole 3D model of analyzed drawing process was generated for FEM calculations, which were carried out using MSC.Marc&Mentat software supplemented with user subroutines and specific external programs. All tools were assumed as rigid bodies, while dimensions of the die for the forming of rectangular part were 147x204 mm. Rectangular blanks (250x200 mm) taken from a sheet of SOLDUR 340 steel with a thickness of 0.93 mm was discretized by 15600 shell elements. Maximum drawing depth amounts to 24.95 mm.

Elastic-plastic calculations, like numerical simulation of springback problem, require the knowledge of Young modulus changes versus plastic strain, which allows more ideal reflection of springback deformation. Therefore the relationship of Young modulus changes versus plastic strain was determined experimentally; detailed description of measurements was presented in (Zimniak, 2005). Briefly, the control software of a tensile test machine allows a calculation in real time of the Young modulus from the coordinates of points (σ, ε). The beginning and the end of the measurements are systematically at the same level of stress, between σ_{min} and σ_{max}, for each specimen. Low rate of the mobile part of the test machine, according to the performance of the acquisition card, permits the measurement of a large number of points between σ_{min} and σ_{max}. Based on the measurement of the Young modulus, we obtain thus a coefficient of linear regression near 0.999. The FEM software, which takes into account the decrease in the Young modulus, gives results very close to experimental values.

The part which is studied is not symmetrical and has different curvatures in different cross sections. The choice of such a part was also motivated by having free surfaces and by small total height. Parts with such features are characterised by high springback deformations, which are difficult to correct through traditional methods. Figure 6 shows a model of punch for forming of complex part with visible different curvatures in different cross sections.

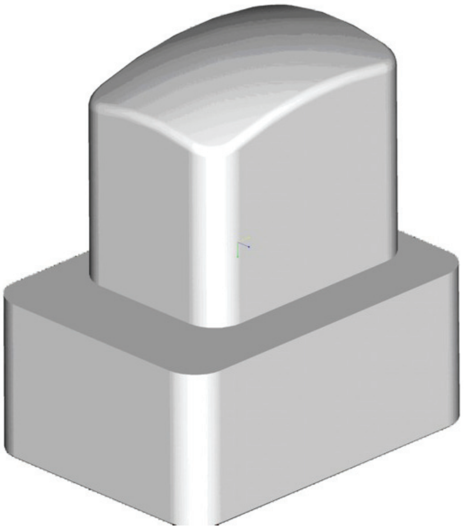

Fig. 6. Model of the punch for forming of a complex part

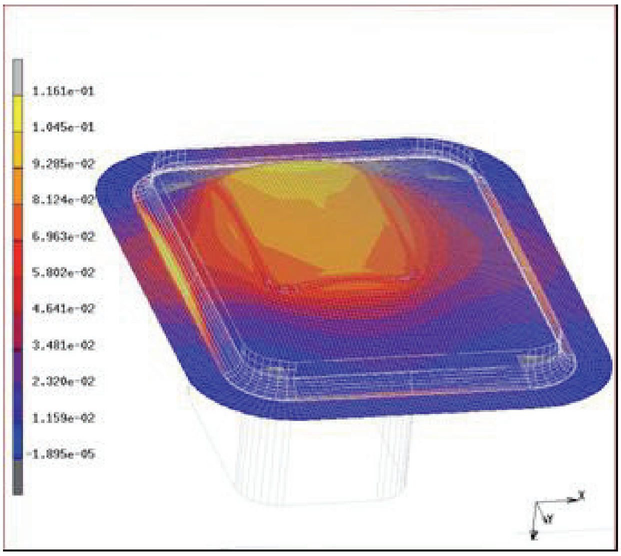

Fig. 7. Distribution of plastic strain intensity for complex part.

The distribution of plastic strain intensity is presented in figure 7 as the result of drawing simulation for maximum punch position.

Figure 8 shows a shape of stamped part obtained after correction. Additionally, theoretical (without shape correction) surface and surface after springback referring to scale up of the edge of the part surface are included. Then corrected tools based on the corrected surface of stamped part were used for experimental testing.

The comparison of theoretical results obtained for the cross section normal to the shorter side of the part (marked circles) with experimental ones for the tools after correction (marked squares) is presented in fig. 9.

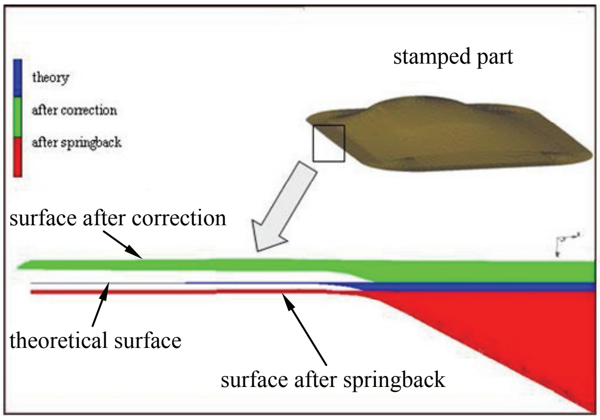

Fig. 8. Shape of the stamped part after correction

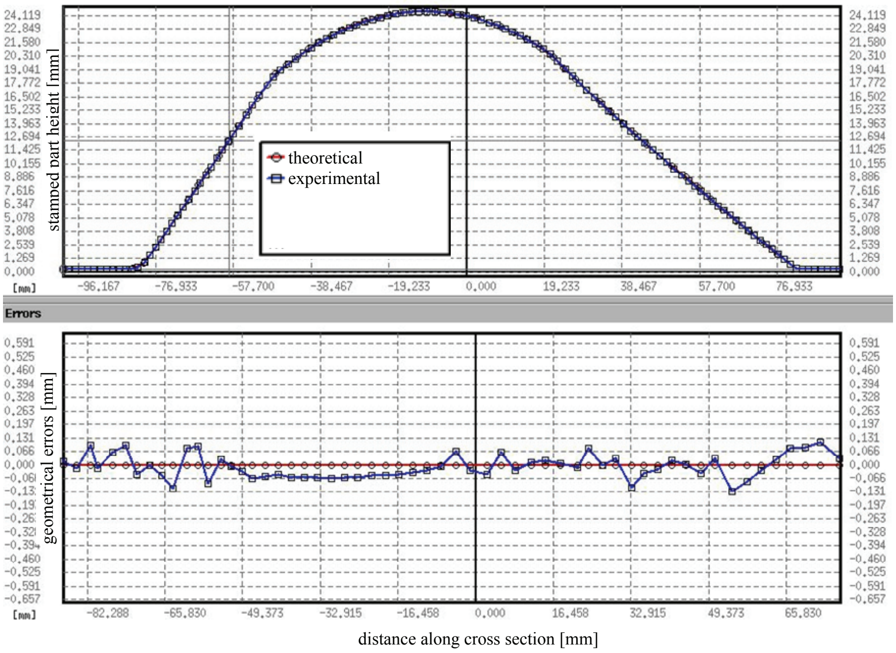

Fig. 9. Comparison of theoretical results for the shorter cross section with experimental results for forming with tools after shape correction. Lower diagram shows geometrical errors determined relative to theoretical shape

The plot of geometrical errors for corrected part, which are determined with respect to the theoretical shape, are included as well. Average shape error for whole corrected part was equal to 0.07 mm. Similar results were received for the cross section normal to longer side of the part. It could be stated that small error of the part's shape confirms the correctness of elaborated tool shape compensation system working.

5. METHODS FOR SHEET METAL FORMING PROCESS CONTROL AND DIAGNOSIS

According to the chart presented in fig. 1, production control and diagnosis module is the last part of the process design system. During mass production some kinds of defects occur at different time intervals. The appearance of defects depends on drawing process parameters, tool wear, sheet material and tribological conditions. Variability of these factors effects the quality of manufactured products directly. Manufacturers need to follow the quality of the part in real time. Such an information could be provided by the system of remote monitoring, which controls the most important dimensions of the part in the normal course and sends them via internet in case of exceeding values. Besides dimensional shape control the system also monitors the possibility of development of part defects such as flow instability or limit sheet metal drawability using magnetic field measurement. Indeed, diagnosis can rely on magnetic measurements thanks to the magneto-mechanical effect known as inverse magnetostriction or Villary effect (Villary, 1965): when loaded mechanically, a ferromagnetic body will induce a magnetic field. And magnetic field sensors allow for an exact determination of the onset of flow instability (Zimniak, 2005). The limit strain value causing an instability is considered to be an appropriate sheet drawability measure. The loss of stability can be determined on the basis of the magnetic field strength H, when it reaches a maximum. However, it is necessary to place the sensor as close as possible to the necking band. An example of a plot of magnetic signal changes (components H_x, H_y), with the marked out point of loss of stability A, is shown in fig. 10.

An automatic method to detect the loss of flow stability was developed. The time interval during which stability is lost can be identified from the plot of magnetic field strength versus time. The advantage of this method – as compared to other tech-

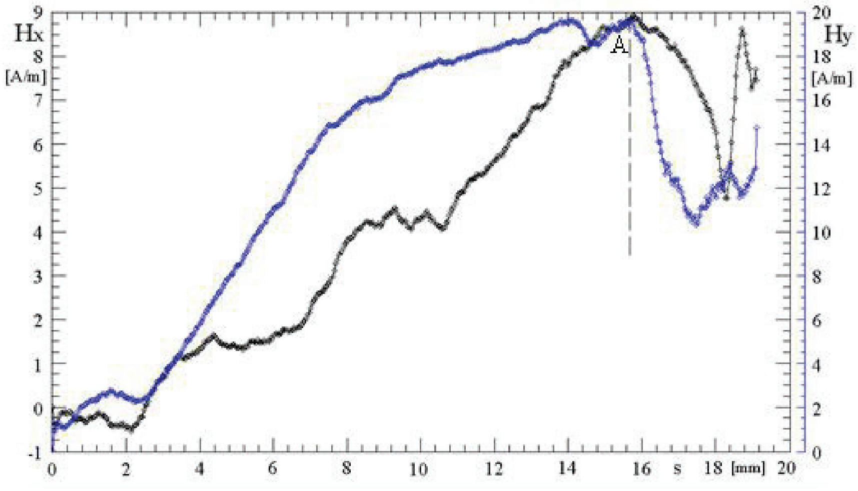

Fig. 10. Magnetic field versus punch displacement

niques - is its accuracy. State-of-the-art magnetic field sensors and magnetovision camera make possible point measurements of the parts and 3-D analyses. A system of remote monitoring of the press forming process, which communicates with the Control Centre via internet, has been developed. Figure 11 shows a remote sheet metal forming process monitoring station.

Fig. 11. Remote sheet metal forming process monitoring station

6. CONCLUSIONS

The following conclusions can be drawn from the research:

1) A drawability assessment system based on forming limit diagrams was incorporated into a finite element method. The forming limit diagrams are determined by a perturbation method. This computer aided design system for sheet metal forming process has given correct results.
2) By applying the perturbation theory to the determination of FLDs good agreement between theoretical FLDs and experimental results for biaxial tension for different materials was obtained. The results would not be as satisfactory with the Marciniak-Kuczyński theory.
3) A computing diagram which exploits the forces acting on the tools during press forming to correct their shape has been developed. The algorithm makes it possible to build a system which assures high quality of the products for both simple and complex press forming operations, including deep drawing, part trimming and die shearing.
4) Neglecting the evolution of Young's modulus with straining is proved to lead to substantial differences.
5) An original method for controlling and diagnosing press forming processes on the basis of measurements of the magnetic field around the part has been developed. The method is based on the magnetic effect which consists in the generation of a magnetic field by a ferromagnetic body subjected to a mechanical load.

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KOMPUTEROWO WSPOMAGANE PROJEKTOWANIE PROCESÓW TŁOCZENIA BLACH

Streszczenie

Opracowano system komputerowego wspomagania projektowania dla procesów głębokiego tłoczenia blach. Bazuje on na metodzie elementów skończonych oraz wprowadzonym do niej systemie oceny tłoczności blach opartym na wykresach naprężeń granicznych. Do wyznaczania teoretycznych wykresów naprężeń granicznych zastosowano teorię perturbacyjną. System umożliwia również korekcję kształtu narzędzi, kompensującą sprężynowanie powrotne wytłoczki w operacjach obejmujących głębokie tłoczenie oraz okrawanie i wykrawanie. W tym celu zastosowano algorytm obliczeniowy wykorzystujący siły działające na narzędzia w trakcie tłoczenia w celu korekcji kształtu narzędzi. Korekcja taka pozwala na uzyskanie dużej dokładności wymiarowo-kształtowej wytłoczek. W celu zapewnienia stałej, wysokiej jakości wyrobów opracowano system kontroli i diagnozowania procesu tłoczenia. W systemie tym zastosowano do określania momentu utraty stateczności materiału metodę, wykorzystującą pomiar pola magnetycznego generowanego w trakcie procesu tłoczenia przez wytłoczkę. Opracowany system zweryfikowano doświadczalnie dla różnego rodzaju blach oraz kształtów wytłoczek. Szerokie stosowanie prezentowanego systemu przyczyni się do znacznych oszczędności oraz poprawy dokładności produkowanych wytłoczek.

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