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Robust Design of Forming Processes

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Properties of raw materials (sheet metal, bars, etc.) used in forming processes are not constant. Other input parameters of forming system (friction conditions, machine settings, temperature, etc.) also scatter considerably during production. Improvement of production processes has always been an important goal in metal forming industry. The aim is to develop cost effective and stabile forming processes where the number of non-conforming products (scrap) is reduced to the minimum. In the first part of the paper an approach is described which enables the user to predict how the scatter of input parameters would influence the final properties of the products. In the second part of the paper the developed approach is used for optimization of forming process with respect to uncontrollable scatter of input parameters with the aim of minimizing scrap ratio. Optimization is based on the use of numerical simulations, response surface methodology and stochastic optimization. It can be performed in the early stage of the production process development cycle. The presented approach was successfully applied in industrial environment during development of technology for forming of various work pieces.

Keywords: forming processes, robust design, numerical simulation, optimization

0 INTRODUCTION

Improvement of production processes has always been an important goal in metal forming industry. The aim is to develop cost effective and stabile forming processes where the number of non-conforming products (scrap) is reduced to the minimum. Numerical simulations are used daily for validation and optimization of forming processes [1] and [2]. They replace physical experiments for reducing costs and speeding up product development. But numerical models are based on the exactly defined constant set of the input parameters (material properties, friction conditions, machine settings etc.), which in reality scatter considerably during production. Technological solutions are therefore achieved without actually understanding exactly how stabile they are. This results in product loss which can be as high as a few percentage of the production volume [3].

Many authors are dealing with the problem of predicting stability of forming processes [3] to [9] but in many cases the approach is too complex and too time consuming for industrial use. The aim of presented research is to develop the simplest possible optimization approach which gives reliable results is the shortest time possible. In practice this means with minimum possible number of numerical simulations. The proposed methodology which consists of numerical simulations, response surface methodology and stochastic optimization is described in Section 1. It was successfully applied during the development of forming procedures for forming of automotive parts. In section 2 it is shown how it is possible to predict scatter of final properties of the product based on scatter in input parameters. In section 3 it is used for optimization of forming process with respect to uncontrollable scatter of input parameters with the aim to avoid high scrap ratio. In the end the results are commented upon and the conclusions are given in Section 4.

1 PROPOSED METHODOLOGY FOR PREDICTION AND INCREASING THE STABILITY OF FORMING PROCESSES

In general metal forming process, the input can be categorized as energy (for powering the press), information (contained by CAD models) and unreformed material (sheet metal, bars, etc.). The response is the deformed product or actually the selected properties of product (e.g. the geometry,

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thinning, final material properties due to hardening of input material, etc.). Also entering the process are control input variables (the variables that can be controlled by the process engineer – for example shape of the forming tool, setting on the forming press) and noise input variables (the variables that cannot be controlled by industrial settings (temperature for example). The control variables, the noise variables and also some of the input variables are stochastic variables.

The presence of stochastic input variables will cause variations of the response - the properties of the products. If the response deviates too much from the intended properties of the products the products may not be acceptable. A stable process is a process which is insensitive to the variations of the stochastic variables influencing the process, i.e. when the expected scatter of the input parameters (material properties and position, machine settings, friction conditions, etc.) do not cause unacceptable properties of the final products [10].

In our research the following approach (integrating numerical simulations, the response surface methodology and stochastic optimization based on Monte Carlo method) was used to study and optimize the stability of the considered stamping process.

1. Numerical models were developed and used for the prediction of the forming processes. Only the critical forming stages were modelled. PAM-STAMP 2G V2004.0 software was used for numerical simulations of stamping processes and DEFORM 2D Ver. 8.2 software was used for numerical simulations of bulk metal forming processes.
2. According to the selected design of experiments numerical simulations were run. Different designs of experiments can be used. In our research a three level Box-Behnken Design of experiments was used. Based on results an empirical model (termed a response function) was developed which approximated the relationship between the response of a system and input variables of the system that affect the response [11]. It is expected that the behaviour of forming system is non-linear therefore a second-order polynomial was used.
3. Based on empirical models, the Monte Carlo simulations were run to find the variation of the studied product properties due to scatter of input parameters [12]. It was assumed that all input variables form a normal distribution.
4. The probabilistic sensitivity of studied output product properties variations to each input parameter scatter was calculated in order to determine the relative magnitude of the effect caused by each input parameter on scatter of final properties. Based on these results a designer is able to select critical input parameters, which have major influence variation of output parameters and can suggest changes in input parameter scatter in a way that the value of studied product properties does not exceed specified tolerances.

2 PREDICTION OF SCATTER OF OUTPUT PARAMETERS

The developed approach was firstly used to predict the scatter of output parameters. Forging of a magnetic core, presented in Figure 1 has been studied as an example. The part had to be forged to the required final shape and it was expected that it would be difficult to keep the scatter of the thickness of the flange *h* within the required tolerance field. Therefore the thickness *h* was selected as the only studied product property.

The studied product was planned to be produced by a multi step forging procedure in 2 presses. Only the forming steps performed in the second mechanical press with nominal force $F_i = 8000$ kN and stiffness of $k = 2.2$ MN/mm were studied without final piercing and cutting steps (see Fig. 2). The material Qst-32-3 was used. The preforms were phosphated and lubricated with Na soap.

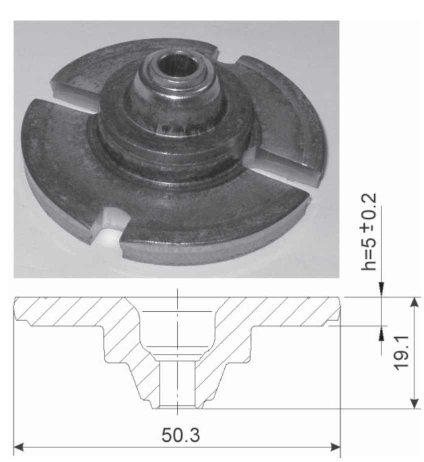

Fig. 1. *Magnetic core*

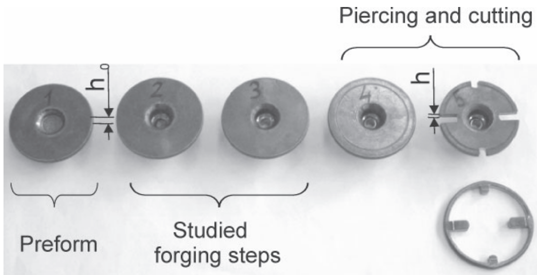

Fig. 2. *Studied forming sequence*

In Table 1 the most important input parameters, their nominal values and expected scatter of values are presented, on the basis of the data previously gathered in the ISKRA Avtoelektrika Ltd. plant [13].

The numerical results, calculated with mean values of input parameters, are presented in Figure 3. The surfaces of the tool parts were defined as rigid. The billet was discretized by elements, representing the material with a plastic constitutive law. The friction between the billet and the tool parts was modelled by the constant shear law. The friction coefficient m = 0.09 was used on the basis of previous experience.

An empirical model was developed which approximated the relationship between the response of a system (height of the flange h) and input variables of the system that affect the response (h_o, R_p, C, n, m). A three level Box-Behnken Design of experiments was used. A part of the design matrix (6 out of 42 runs) can be seen in Table 2. The advantage of this design is that fewer runs are required to obtain quadratic response function in comparison with other designs.

Heights of the flange h, which can also be seen in the left column of Tab. 2, were estimated by taking into account the forming forces, predicted by numerical simulations and measured stiffness of the press. Then a quadratic response function presented by equations (1) was calculated. The response function coefficients had been determined by a standard method of least squares, which minimizes the sum of the squared deviations of fitted values:

$$\begin{aligned} h =\ & -2.57736+3.14615\cdot h_0-2.75319\cdot 10^{-3}\cdot R_p \\ & -5.35512\cdot 10^{-3}\cdot C-1.63355\cdot n-10.77242\cdot m \\ & -0.32937\cdot h_0^2+1.71602\cdot 10^{-6}\cdot R_p^2+2.29794\cdot 10^{-7}\cdot C^2 \\ & -1.84732\cdot n^2+13.4623\cdot m^2+3.6378\cdot 10^{-4}\cdot h_0\cdot R_p \\ & +1.06929\cdot 10^{-3}\cdot h_0\cdot C+0.81315\cdot h_0\cdot n \\ & +0.062976\cdot h_0\cdot m-4.04583\cdot 10^{-7}\cdot R_p\cdot C \\ & -9.0494\cdot 10^{-3}\cdot R_p\cdot n+0.010795\cdot R_p\cdot m \\ & -1.15119\cdot 10^{-3}\cdot C\cdot n+5.65905\cdot 10^{-3}\cdot C\cdot m \\ & +8.05595\cdot n\cdot m \end{aligned} \qquad (1).$$

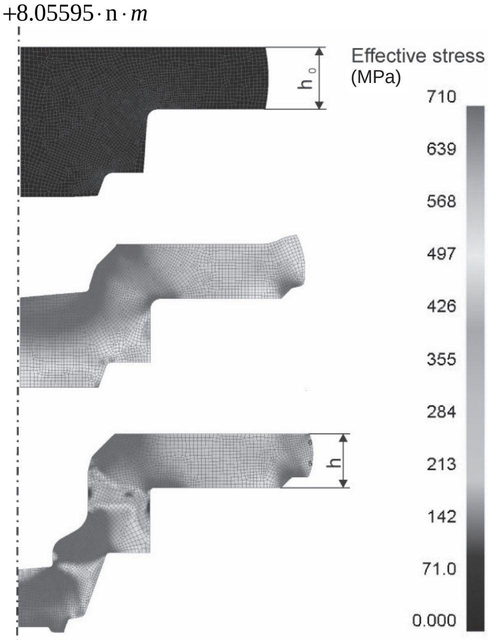

Fig. 3. *Numerical simulation of forging process*

Table 1. *Expected scatter of input parameters*

Input parameter	Mean value and expected scatter
Height out of 1st press [mm]	h_0 = 6.1±0.1
Yield stress [MPa]	R_p = 400±40
Hardening coefficient [MPa]	C = 676±50
Hardening exponent	n = 0.165±0.02
Coefficient of friction for constant shear law	m = 0.09±0.01

where C and n are coefficients used in hardening law $\sigma_f = C\cdot\varphi^n$

Table 2. *Experimental design matrix and results of numerical simulations*

Run						h
	h_0	R_p	C	n	m	
1	6.1	440	726	0.1685	0.09	5.080
2	6.2	400	676	0.1685	0.1	5.020
3	6.2	400	676	0.1885	0.09	4.985
4	6	400	676	0.1885	0.09	4.959
5	6.1	400	676	0.1685	0.09	5.002
42	6	400	726	0.1685	0.09	5.071

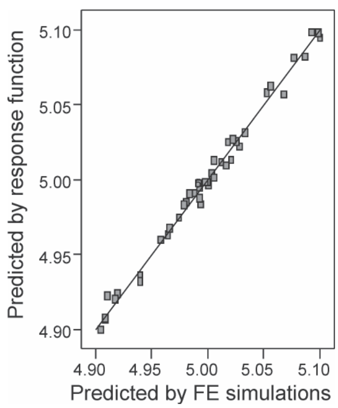

Fig. 4. *Predicted versus actual response*

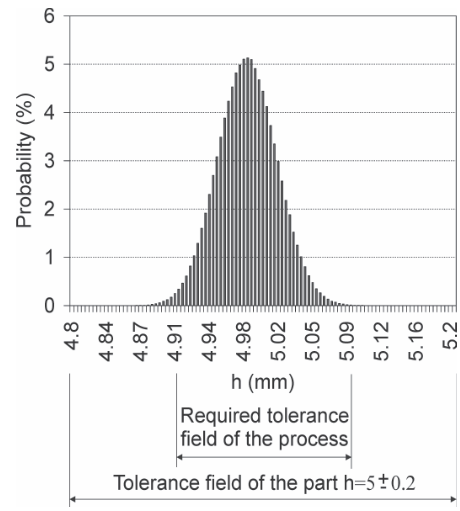

Fig. 5. *Probability chart for predicted h*

In Figure 4 the response of the system predicted by numerical simulations is compared to the one predicted by equation (1). It can be seen that equation (1) predicts the response of the system with good reliability.

Once the response function was obtained, the Monte Carlo techniques were used to extract the statistical distribution of the studied response for a specific set of statistical variations of input parameters. It was assumed that the variations of all input parameters are normally distributed with a mean value and standard deviation σ equal to 1/6 of the expected scatter specified in Table 1. Figure 5 shows the predicted probability chart for the scatter of the studied flange dimension *h*.

The required tolerance of the height of the flange *h* is ±0.2 mm. On the basis of the results of stochastic modelling it is predicted that practically 100% of the parts produced would be within the required tolerance. But in real production the whole tolerance field cannot be used only to compensate for the scatter of input parameters (dimensions, material properties and friction) listed in Table 2. The forging tools wear out during the production. Therefore they are produced with dimensions that allow maximum possible tool life and production is not carried out in the middle of the tolerance fields. Another reason is that customers of the forged products expect that only with a small percent of forged products the dimensions will be close to the limits of the requested tolerance fields. In industrial practice for the parts similar to the one presented in the paper, the scatter of dimension *h* during the test production process must be lower than ±0.1 mm in order to assure a stable large batch production over the time. For such requirement it is predicted in Figure 5 that the scatter of dimension *h* could be critical. During the trial production flange dimensions *h* of all test pieces were between 4.955 and 5.052 mm.

Figure 6 shows the sensitivity chart for the part attribute h, which was calculated based on the contribution of each input parameter to variance. The purpose of this is to determine, which input parameters significantly affect the studied part dimension. It provides us the ability to quickly judge the influence of the scatter of each input parameter on the studied part dimension.

From the Figure 6 the following conclusions can be extracted:

1. Studied dimension h is most sensitive to variations of the hardening properties of the material *C* and *n*.

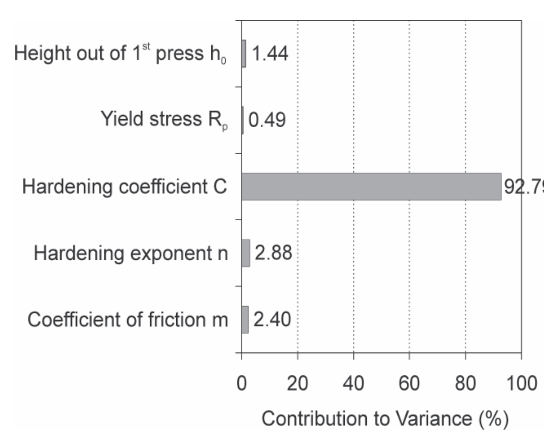

Fig. 6. *Sensitivity chart for predicted h*

2. Variations of coefficient of friction m and flange height after the first pass h_0 are of minor importance.
3. The scattering of Yield stress R_p is not very important.

In order to reduce the amount of rejected parts after the forging process it is reasonable to reduce the scatter of hardening properties of the material *C* and *n*. If this is too costly to achieve it is also possible to use the mechanical press with higher stiffness to produce the performance in the first pass. By this the scatter of flange height after first pass h_0 can be reduced.

3 OPTIMIZATION OF FORMING PROCESS AIMING AT MAXIMUM ROBUSTNESS

In some cases it is not enough only to predict the scatter of final properties of product, but it is also necessary to optimize the production process. Stamping process for production of part, whose geometry and approximate dimensions are presented in the upper part of Figure 7, was studied. In this case the object of study was prediction of reject rate and optimisation of stamping procedure. The selected stamping procedure is presented in the lower part of Figure 7. Drawbead was planned in stage 2 to prevent wrinkling in the walls of the part. The two main input parameters which could be optimized during development of forming procedure were: the initial shape of the blank (size of the cut-out produced in stage 1, defined by parameter *a*), and properties of drawbead (defined by restraining force F_{db}). If the cut-out is big and restraining force F_{db} is low then material flow into the die cavity is less constrained and only minor sheet thinning but higher wrinkling is expected. On the other hand if the cut-out is small and restraining force F_{db} is high, then material flow into the die cavity is more constrained and lower wrinkling but danger of excessive sheet thinning and localization is expected.

Table 3. *Expected scatter of input parameters*

Input parameter	Mean value and expected scatter
Initial sheet thickness (mm)	$s_0 = 0.7 \pm 0.05$
Yield stress (MPa)	$R_p = 152 \pm 45$
Hardening coefficient (MPa)	$C = 373 \pm 50$
Hardening exponent (1)	$n = 0.218 \pm 0.036$
Coefficient of anisotropy	$r = 2.12 \pm 0.2$
Coulomb's coefficient of friction (1)	$\mu = 0.1 \pm 0.015$

In Table 3 the most important input parameters, their nominal values and expected scatter of values are presented, based on of the data previously gathered [10] and on industrial experience.

The optimum solution was searched for within the following search space: cut-out *a* = 0 to 90 mm and restraining force F_{db} = 0.02 to 0.08 kN/mm. If *a* equals 0, no cut-out is produced at all and *a* should not be greater than 90 mm, otherwise there is not enough material in the blank to form the product with the required dimensions. Restraining force F_{db} = 0.02 kN/mm can be ensured by a modest drawbead and restraining force F_{db} = 0.08 kN/mm can be ensured by strong drawbead.

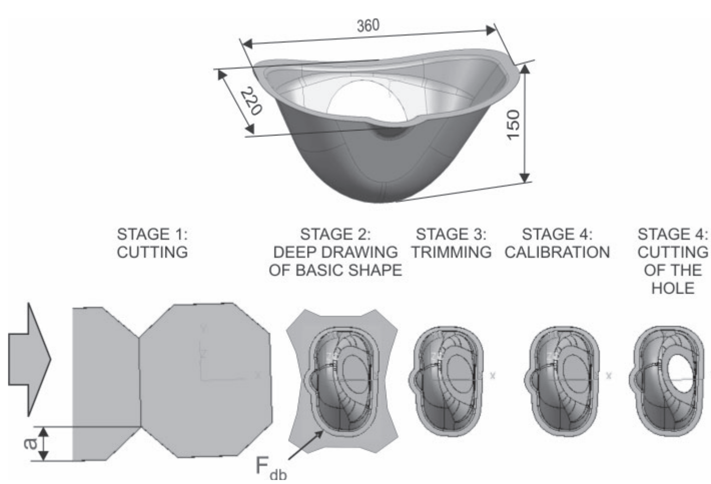

Fig. 7. *CAD model of the studied part and selected forming procedure*

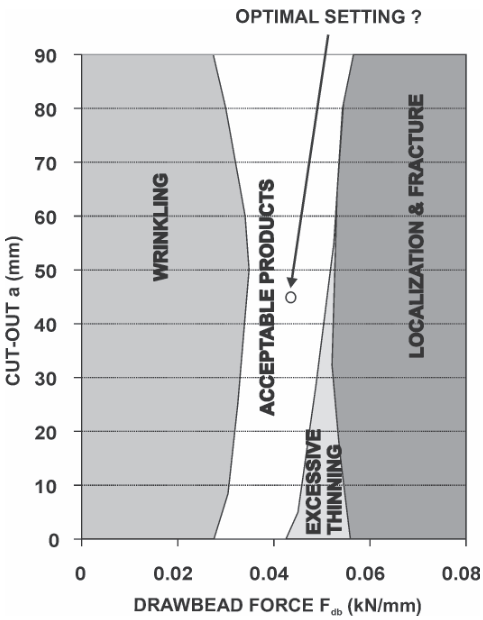

Fig. 8. *Technological window for the studied stamping process*

In metal forming, the combination of input parameters leading to a successful forming operation and acceptable products is defined as a technological window of the process. For the studied example, where the only two input parameters that could be varied were the following: the size of the cut-out a and the drawbead force F_{db}, therefore the technological window can be easily determined by several numerical simulations or experimental trials (see Fig. 8).

The questions arose how to evaluate and how to maximize the stability of the forming process. What is the optimum size of the cut-out and what is the optimum setting of the drawbead force F_{db} for the maximum stability? Intuitively, it would be reasonable to set parameters exactly in the middle of the technological window. But is this really the best solution?

The following approach was used to answer this question. A numerical model and the results calculated with average input parameters are presented in Figure 9. The surfaces of the tool parts were defined as rigid. The blank sheet was discretized by quadrangle elements, representing the material with an elasto-plastic constitutive law. For the material hardening determination the Krupkowski law was used. The friction between the blank and the tool parts was modelled by the Coulomb's Law. Prediction of localization was done by comparing the strain states to the Forming Limit Curve (FLC) that was determined as described in [14]. Prediction of wrinkling was done by comparing the heights of the wrinkles to the selected critical value. The allowed thinning was selected to be 20% for the studied example in compliance with the requirements of the customers from automotive industry.

For better understanding of the results it is reasonable to define the response of the system by Equation (2), which evaluates the danger of the unwanted output properties:

$$D\,(a, F_{db}) = \max\,(D_L, D_T, D_W)$$
$$D_L = \frac{\varepsilon}{\varepsilon_{FLD}}\ ;\ D_T = \frac{s_0 - s}{s_0 - s_{\min}}\ ;\ D_W = \frac{h_w}{h_{w\max}} \qquad (2).$$

D_L is defined as the danger of localization, D_T is defined as the danger of extensive thinning, D_W is defined as the danger of wrinkling, ε is the critical actual strain path (shown in Fig. 9), ε_{FLD} the allowed

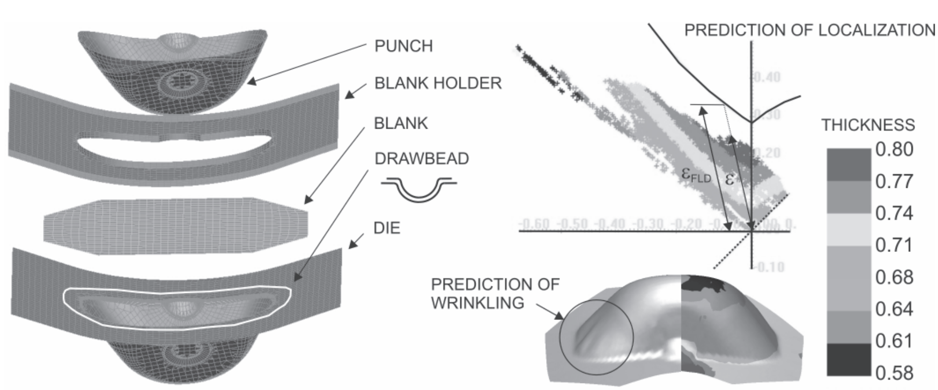

Fig. 9. *Numerical model and results*

strain path (shown in Fig. 9), s_0 the initial sheet thickness, s sheet thickness at the product, s_{min} allowed minimum final sheet thickness, h_w the height of the wrinkles detected on the product and $h_{w\,max}$ allowed height of the wrinkles. Finally D is defined as the parameter predicting the danger that any of the unwanted output properties will occur. If the value D is low, the technological safety is high. In the case of D>1 the product is unacceptable (at least one of the unwanted output properties occurs). In our research a three level Box-Behnken Design of experiments was used. Later the empirical models (termed the response functions) were developed, which approximated the relationship between the response of a system (danger of localization, excessive thinning and wrinkling) and input variables of the system affecting the response. Response functions are given by:

$$\begin{aligned}\mathrm{Ln}\,D_L =& -32.064+111.136\cdot F_{db}-0.240\cdot a-79.673\cdot s-0.301\cdot R_p\\ &+0.147\cdot C-334.126\cdot n+76.087\cdot r+215.998\cdot\mu+942.625\cdot F_{db}^2\\ &-5.203\cdot10^{-5}\cdot a^2-14.662\cdot s^2+2.306\cdot10^{-5}\cdot R_p^2+3.185\cdot10^{-6}\cdot C^2\\ &+28.484\cdot n^2-0.209\cdot r^2-148.556\cdot\mu^2-0.230\cdot F_{db}\cdot a+123.445\\ &\cdot F_{db}\cdot s-0.338\cdot F_{db}\cdot R_p-0.049\cdot F_{db}\cdot C+115.446\cdot F_{db}\cdot n-\\ &82.454\cdot F_{db}\cdot r-186.487\cdot F_{db}\cdot\mu+0.160\cdot a\cdot s+1.645\cdot10^{-4}\cdot a\cdot R_p\\ &-1.967\cdot10^{-4}\cdot a\cdot C\end{aligned}\tag{3}$$

$$\begin{aligned}\mathrm{Ln}\,D_T =& -86.568-30.745\cdot F_{db}-0.207\cdot a+1.609\cdot s+0.061\cdot R_p\\ &+0.270\cdot C-39.125\cdot n+39.849\cdot r+2.893\cdot\mu+755.905\cdot F_{db}^2\\ &+1.906\cdot10^{-6}\cdot a^2+17.309\cdot s^2+8.397\cdot10^{-5}\cdot R_p^2-2.879\cdot10^{-4}\cdot C^2\\ &+63.085\cdot n^2+1.690\cdot r^2+636.884\cdot\mu^2-0.092\cdot F_{db}\cdot a+119.264\cdot F_{db}\cdot s\\ &-0.254\cdot F_{db}\cdot R_p+0.039\cdot F_{db}\cdot C-62.648\cdot F_{db}\cdot n-2.614\cdot F_{db}\cdot r\\ &-462.911\cdot F_{db}\cdot\mu+0.132\cdot a\cdot s-1.275\cdot10^{-4}\cdot a\cdot R_p+5.629\cdot10^{-5}\cdot a\cdot C\end{aligned}\tag{4}$$

$$\begin{aligned}\mathrm{Ln}\,D_W =& +16.052+50.031\cdot F_{db}-0.125\cdot a+43.156\cdot s-1.163\cdot10^{-3}R_p\\ &+0.039\cdot C-71.520\cdot n+8.190\cdot r-642.077\cdot\mu+251.456\cdot F_{db}^2\\ &-1.304\cdot10^{-4}\cdot a^2-84.569\cdot s^2+2.619\cdot10^{-5}\cdot R_p^2-7.516\cdot10^{-5}\cdot C^2\\ &-133.624\cdot n^2-1.079\cdot r^2-1870.281\cdot\mu^2-0.030\cdot F_{db}\cdot a+45.461\cdot F_{db}\cdot s\\ &+0.248\cdot F_{db}\cdot R_p+0.177\cdot F_{db}\cdot C-485.248\cdot F_{db}\cdot n+13.555\cdot F_{db}\cdot r\\ &-1545.954\cdot F_{db}\cdot\mu-0.010\cdot a\cdot s+1.712\cdot10^{-4}\cdot a\cdot R_p+4.355\cdot10^{-5}\cdot a\cdot C\end{aligned}\tag{5}$$

Once the response functions were obtained, the Monte Carlo techniques were used for the determination of the optimal setting of input parameters a_{opt} and $F_{db\,opt}$.

The results of the optimization procedure are presented on the left hand side of Figure 10. It is predicted that maximum stability (minimum reject rate) can be achieved when the forming procedure is performed with the settings a_{opt} = 70 mm and $F_{db\,opt}$ = 0.04 kN/mm. The forming tool was produced with regards to the results given above. It is presented on the right hand side of Figure 10. After the preliminary testing in the tool manufacturing company it was decided that the geometry of the drawbead, which provides restraining force F_{db} = 0.04 kN/mm, would be selected appropriately, but the cut-out produced in stage 1 would be 20 mm higher that the theoretically calculated optimum choice.

Finally Figure 11 shows the sensitivity chart for the danger of the unwanted output properties D which was calculated based on the contribution of each input parameter to variance. It provides us with the ability to quickly judge the influence of the scatter of each input parameter to the studied process stability.

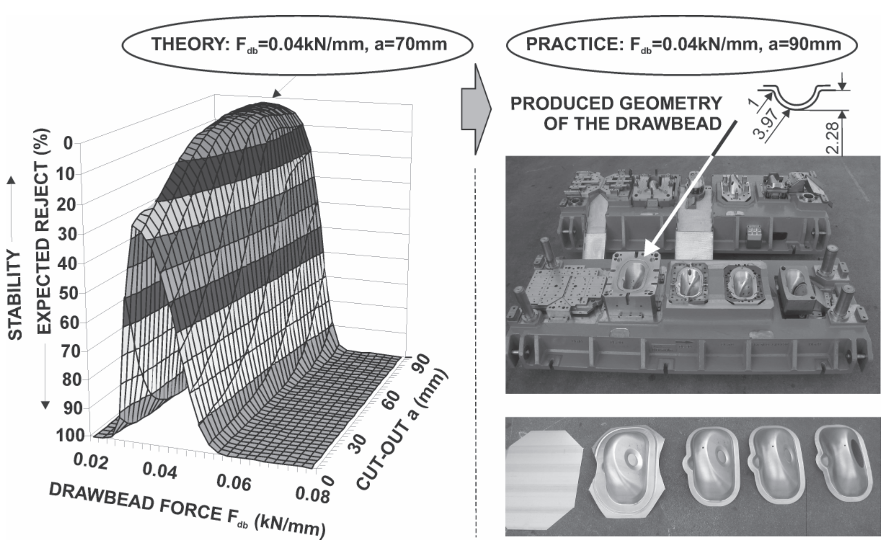

Fig. 10. *Results of the optimization procedure*

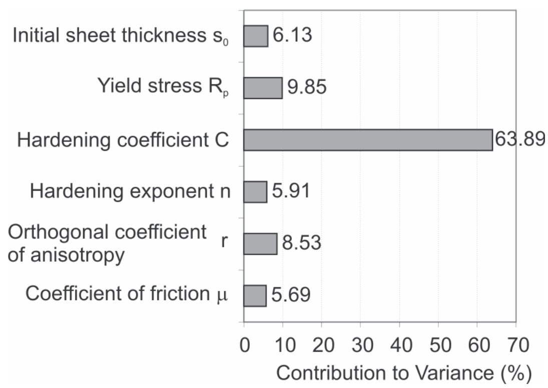

Fig. 11. *Sensitivity chart for the predicted stability*

From the Fig. 11 the following conclusions can be extracted:

1. Process stability is most sensitive to variations of the hardening properties of the material (especially hardening coefficient *C*).
2. Variations of other input parameters (initial sheet thickness, yield stress, orthogonal coefficient of anisotropy and coefficient of friction) are of minor importance.

4 DISCUSSION AND CONCLUSIONS

Manufacturing processes consist of variability which can deteriorate product quality and increase costs. The process of generating experimental data in the early stage of production process development is quite difficult. For such cases numerical simulation can be directly applied for generating the experimental data. In the paper the approach that can help to predict and optimize the forming processes from the stability point of view is presented. It gives feedback and direction for design improvement.

Using this approach the optimization process can be performed with the minimum number of time-consuming numerical simulations. The method is simple, appropriate for industrial use. It is especially appropriate for cases where the number of input parameters taken into account is relatively low (lower that 10). In such cases it gives excellent results with low number of required (and for complex industrial examples many times quite time consuming) numerical simulations. For solving the cases where the number of input parameters is higher the number of numerical simulations required becomes large no matter which design of experiments is used. In such cases other optimization approaches give results faster. Only the so called "technological reject" is evaluated. The reject resulting from other reasons (failure of the tool, wrong setting of the machine, etc.) is not the subject of the presented paper.

In order to confirm the presented results of optimization, the mass production with different settings of input parameters should be observed. In industrial practice this is impossible to achieve since companies are unwilling to perform changes on the tool and run the production with undesirable settings just to measure the increase of the reject rate. But the experts from the production floor were satisfied with the presented calculations and results.

In future the cost function must be integrated into the optimization procedure in order to correctly optimize the studied production processes from the economical point of view. For example, in some cases it is reasonable to use cheaper raw material with higher scatter of properties although the production is performed with higher scrap ratio.

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