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STUDIES FOR THE REDUCTION OF SPRINGBACK IN SHEET METAL FORMING

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Abstract: The automation of the industrial processes has lead to an increasing need for more precise parts. This is more evident in the automotive industry where numerous parts are manufactured by plastic forming. The most important faults in sheet metal formed parts are springback, wrinkling and tearing. This paper presents some studies for the optimization of the forming process in order to reduce the effects of springback. The proposed method uses the response surface methodology applied to the U-bending test.

1. INTRODUCTION

Accurate prediction of springback of metal sheets is of vital importance for the design of tools in automotive and aircraft industries. The springback will occur after removing the applied loads from the deformed sheet, resulting in the deviation of the product from the applied tooling shape.

Application of optimization techniques to metal forming problems [1, 2, 3] leads often to high numbers of expensive function evaluations. This is particularly the case when cost and constraint functions are obtained via complete finite element simulations involving fine meshes, high numbers of degrees of freedom, nonlinear geometrical and material behavior. Response surface methodology (RSM) is used as an alternative method [3, 4] for replacing a complex model by an approximate one based on results calculated at various points in the design space. RSM can thus be used to diminish the cost of functions evaluation in structural optimization. The optimization is then performed at a lower cost over such response surfaces. RSM are well established for physical processes as documented by Myers and Montgomery [3] while the applications to simulation models in computational mechanics form a relatively young research field.

2. PROBLEM FORMULATION

2.1. FORMULATION OF THE OPTIMIZATION PROBLEM

In the optimization process, the goal is to minimize a function $\Phi(x)$, $x \in R^n$ subjected to a number of constraints $g_j(x) \le 0,\ j=\overline{1,m}$, with $L_i \le x_i \le U_i,\ i=\overline{1,n}$, where Φ represents the cost function, x_i are design variables and g_j is the j-th nonlinear constraint. L_i and U_i are the lower and upper bounds of the design variables and define the interest interval. The RSM approach consist in solving a problem where the cost function and the constraint functions are replaced by some approximations $\tilde{\Phi}$ and $\tilde{g}_j$. The problem may be written as:

$$\text{minimize } \tilde{\Phi}(x) \text{ subjected to constraints } \tilde{g}_j(x) \le 0,\ j=\overline{1,m} \quad (1)$$

The approximations are based on a set of numerical experiments with the function Φ. The problem of distributing the experimental points in the design space is known as “design of experiments” (DOE).

Knowing the function values for a set of experimental points x_i distributed according to a certain DOE, the function $\tilde{\Phi}$ may be defined in terms of basis functions *p* and some adjusting coefficients *a* as:

$$\tilde{\Phi}(x) = p^T(x)a(x) \tag{2}$$

Generally, the basis function are modeled as polynomials, so the $\tilde{\Phi}$ function may be written as:

$$\tilde{\Phi}(x) = \left\langle 1 \quad x_1 \quad x_2 \quad \ldots x_n \quad x_1x_2 \quad \ldots x_ix_{i+1} \quad \ldots \frac{x_1^2}{2} \quad \ldots \frac{x_n^2}{2} \right\rangle \begin{Bmatrix} a_0 \\ a_1 \\ M \\ a_n \end{Bmatrix} \tag{3}$$

The coefficients a_i are determined by a weighted least squares method minimizing the error between the experimental and approximated values of the objective function:

$$J(a) = \sum_{i=1}^{N} w(\|x_i - x\|)\left(p^T(x_i - x)a - \Phi(x_i)\right)^2 \tag{4}$$

where N is the number of experiments and x_i are the experimental designs.

The weights w_i insure the continuity and the locality of the approximation and are defined $w_i > 0$, decreasing within a fixed region around the point *i* called the domain of influence of x_i and vanish outside. The weight function are determinant by influencing the way that the coefficients a_i depend on the location of the design point *x*.

$\min(J)$ gives

$$a(x) = A^{-1}Bf \tag{5}$$

with

$$A = PWP^T \qquad B = PW \tag{6}$$

where

$$P = [\ldots p(x_i - x)\ldots],\ W = \begin{bmatrix} w(x_1 - x) & & 0 \\ & w(x_2 - x) & \\ 0 & & w(x_n - x) \end{bmatrix} \tag{7}$$

By construction, the approximation represents exactly the basis functions p_i. The a_i may be interpreted as the coefficients of Taylor expansion of Φ around the evaluation point *x*.

2.2. SPRINGBACK SIMULATION FOR U-BENDING

Springback parameters that were observed during the analysis are presented in fig. 1:

- sidewall radius ρ;
- bottom angle θ_1;
- flange angle θ_2;
- bottom profile radius R_b;

- flange profile radius Rf.

The simulations considered a plane strain state and because of the symmetry only half of the assembly was modeled. The geometrical model and tools dimensions are presented in fig. 2. The initial dimensions of the sheet are 350 mm length, 30 mm width and 0.8 mm thick. The sheet was considered deformable body and the model used shell elements (S4R) on one row with 5 integration points through the thickness. The tools (punch, die and blankholder) were modeled as rigid because they have the advantage of reduced calculus efforts and a good contact behavior. The material is a mild steel that was modeled as elasto-plastic, where elasticity is considered isotropic and plasticity is modeled as anisotropic using Hill quadratic anisotropic yield criterion. As only half of the assemble was modeled, a symmetry condition was necessary. The boundary conditions imposed to the tools were intended to describe the experimental conditions as accurate as possible. For contact conditions a modified Coulomb friction law combined with penalty method was used.

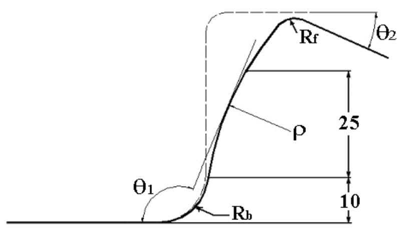

Fig. 1 Geometrical springback parameters

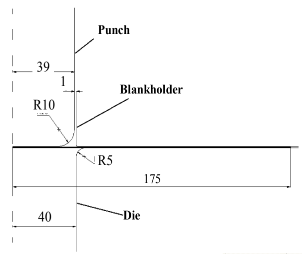

Fig. 2 Geometry of the simulation model

3. PROCESS OPTIMIZATION

For the optimization of the process three parameters with two variation levels were considered, the blankholder force, punch radius and die radius (Table 1). The objective was to minimize the opening of the final part. The objective function represents the maximum opening distance

$$\Phi = \max \|d_i\| \tag{8}$$

where, d_i represents the distance at each node from the opened final part to its original position from the end of the forming operation (fig. 3).

Table 1. Variation field of the parameters

Parameters	Minimum value (-1)	Maximum value (+1)
A: Blankholder force F [kN]	40	200
B: Punch profile radius R_p [mm]	10	12
C: Die profile radius R_m [mm]	5	6

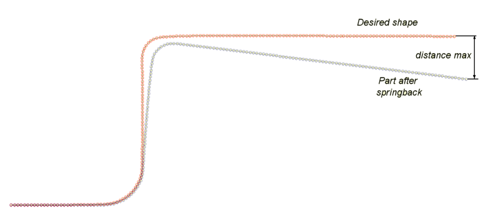

Fig. 3. Part before and after springback

The optimization module of Design-Expert searches for a combination of factor levels that simultaneously satisfy the requirements placed on each of the influencing process parameters and geometrical parameters of the part. The conditions are combined into an overall desirability function and the program seeks to maximize this function. Optimization of the forming problem was carried using central composite design (CCD) formulation of the response surface method. CCD's are designed to estimate the coefficients of a quadratic model. All point descriptions will be in terms of coded values of the factors.

The experiments table is presented in fig. 4. Based on the analysis of the results the objective function is modeled as quadratic.

Std	Run	Block	Factor 1 A:Blankholder kN	Factor 2 B:Punch radius mm	Factor 3 C:Die radius mm	Response 1 Objective mm
6	1	Block 1	200.00	10.00	6.00	5.312
4	2	Block 1	200.00	12.00	5.00	2.51
19	3	Block 1	120.00	11.00	5.50	10.548
14	4	Block 1	120.00	11.00	6.34	4.739
7	5	Block 1	40.00	12.00	6.00	9.412
10	6	Block 1	254.54	11.00	5.50	13.293
9	7	Block 1	-14.54	11.00	5.50	9.862
12	8	Block 1	120.00	12.68	5.50	7.841
8	9	Block 1	200.00	12.00	6.00	14.263
15	10	Block 1	120.00	11.00	5.50	10.548
13	11	Block 1	120.00	11.00	4.66	2.952
5	12	Block 1	40.00	10.00	6.00	11.328
16	13	Block 1	120.00	11.00	5.50	10.548
18	14	Block 1	120.00	11.00	5.50	10.548
11	15	Block 1	120.00	9.32	5.50	8.326
2	16	Block 1	200.00	10.00	5.00	4.14
1	17	Block 1	40.00	10.00	5.00	11.459
3	18	Block 1	40.00	12.00	5.00	7.803
20	19	Block 1	120.00	11.00	5.50	10.548
17	20	Block 1	120.00	11.00	5.50	10.548

Fig. 4. Table of experiments

The analysis of variance (ANOVA) shows that the model is significant and gives the equation of the model:

$$
\begin{gathered}
Objective = -398.009 - 3.979A - 170.385B + 583.803C - \\
-82.268C^2 + 0.179AB + 0.356AC + 27.223BC
\end{gathered}
\qquad (9)
$$

The optimization is carried out using global optimization procedure. The desirability of the solution is 0.805 from a possible 1. The response surface model is presented in fig. 5.

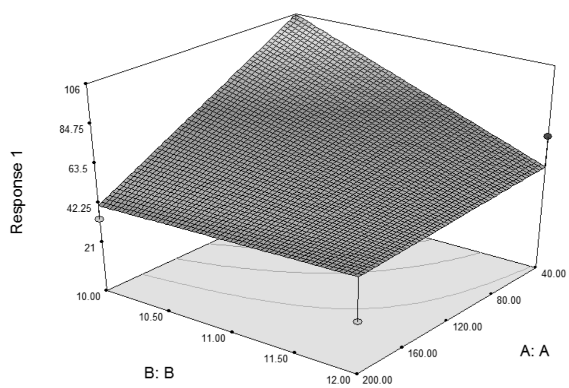

Fig. 5. Objective function

The program determined the following optimal process parameters:

- blankholder force *F=199.73 kN*;
- punch profile radius R_p*=10 mm*;
- die profile radius R_m*=5* mm;

The estimated value of the objective function is Φ = 41.728.

For the verification of the results, a simulation by finite element method was made using ABAQUS software using as input data the above process parameters. The objective function resulted with the value Φ = 42.869, which is in relative good agreement with the estimation.

4. CONCLUSIONS

An optimization of the forming process using response surface method was proposed. The resulting response surface algorithms involve iterative improvement of the objective and constraint functions employing locally supported nonlinear approximations.

The methodology conducted to rather good results but may be improved by using more variables with more variation levels. Thus, the new methods needs to be further tested on larger examples with more design variables and nonlinear constraints.

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