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Numerical modelling of springback behavior in folding process

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Abstract. Through experimental and numerical studies of metal forming processes by plastic deformation, this paper represents a numerical simulation by finite element of the mechanical behavior of the material during a permanent deformation phenomenon. The main interest of this study is to optimize the shaping processes such as folding. In this context the elastic return for the folding process has been further reduced by using the design of experiments approach. In this analysis, it is proposed to consider the following factors: bending radius, metal-sheet thickness, gap and length of the fold.

Keywords: design metal forming processes; elastic return; optimization of experiments

1. Introduction

In general, facing the resolution of an optimization problem, the objective function must be defined, the "elastic return" as the function response in this case, that will be optimized as a function of parameters. Folding is forming process by cold deforming, which consists of deforming a flat sheet by changing abruptly the angle. Therefore, there is inevitably an elastic deformation that accompanies it, as the elasticity value of the material can be exceeded in the folding processes, but not the limits of elastic force. In other word, the material retains some of its original elasticity and consequently the material tries to return to its original shape and bent slightly, when the load is removed from it, Andersson (2001). The main goal of the study is to develop a numerical and experimental simulation tools for sheet metal forming processes. In fact, the numerical prediction of processes has become almost inevitable on an industrial-scale; Areas for improvement relate more specifically to: folding new materials, a better prediction of the geometrical differences related to the elastic return of the material when the tools are removed and, the numerical simulation of post-formatting operations, Besse (2003). An application of the numerical plan method (factorial plan) is presented in the case of folding, in advance the elastic returns or cracks that may occur during the procedure.

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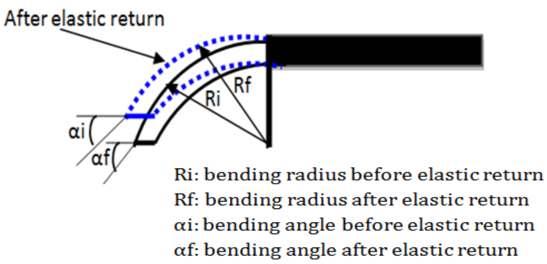

Fig. 1 Elastic return

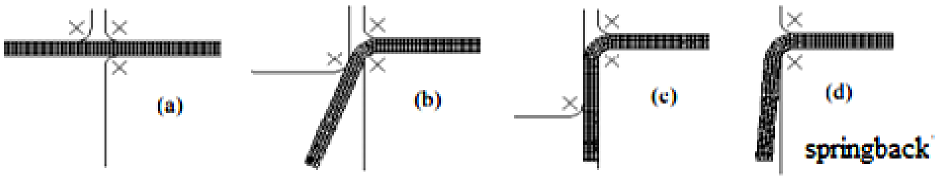

Fig. 2 Numerical simulation of folding process

2. Elastic return

When the stress is removed, during the shaping by folding process, the sheet metal attempts to return to its original shape, due to the residual stresses induced in this last. This phenomenon, depending on the properties of the material and the configuration of the tools, is known as elastic return, Boulmane (1994), Bathe and Dvorkin (1985).

3. Numerical model

The springback prediction was conducted using ABAQUS software, as shown by the numerical model in Fig. 2. The experiments are conducted on steel sheets of 3 and 4 mm of thickness. The sheet metal is specified in the numerical simulations by the value of Young's modulus, $E = 210$ GPa, Poisson's ratio $\nu = 0.3$, elastic limit $\sigma y = 250$ MPa, bulk modulus $K = 1045$ MPa, and strain hardening exponent $n = 0.2$. Since the sheet metal is the point of interest, the sheet is meshed using three and Four-node bilinear plane strain elements (CPE3 and CPE4). The rigid material properties are given for bending dies (Lepadatu 2006).

4. Design of experiments

Usually, design of experiments method is applied as a function of real experiments, for which the modification of the experimental conditions corresponds to more or less important variations in the response to be studied. In this approach, and as the initial condition is a numerical refining, the obtained results of numerical simulation (Table 1), can be modeled by the design of experiments method. The identification of possible causes, that may cause the elastic return, requires the control of the given factors in Table 2.

Table 1 Characteristics of the response (Elastic return)

Description	Unit of measure	Results
Elastic return	0°	Y

Table 2 Factor characteristics

Description	Niveau bas	Niveau haut
Bending radius (mm)	04	06
Metal-sheet thickness (mm)	03	04
Gap (mm)	01	03
Length of the fold (mm)	50	70

4.1 Experimental results

In the table below, the experimental results of the variation of elastic return as a function of folding radius, sheet thickness and, gap and length of the fold are presented. It should be noted that these results were obtained during the research works in reference (Lepadatu 2006).

The full factorial design is theoretically perfect for a screening study, but the time and experimentation costs become important, once the factors exceeds Andersson (2005). In our case, the experiments are numerical simulations, so this disadvantage does not have to be. Since all factors have two levels for each of them. The number of experiments (N) or simulations required for all combinations can be easily calculated by the expression. $N = 2^K$ (K: is the number of factors).

Table 3 Full factorial design

N	Bending radius	Metal-sheet thickness	Gap	Length of the fold	Y(Elastic return)
01	4	3	1	50	2.7433
02	6	3	1	50	3.1858
03	4	4	1	50	2.5727
04	6	4	1	50	2.8683
05	4	3	3	50	3.0503
06	6	3	3	50	3.4928
07	4	4	3	50	2.8797
08	6	4	3	50	3.1753
09	4	3	1	70	2.7433
10	6	3	1	70	3.1858
11	4	4	1	70	2.5727
12	6	4	1	70	2.8683
13	4	3	3	70	3.0503
14	6	3	3	70	3.4928
15	4	4	3	70	2.8797
16	6	4	3	70	3.1753

Table 4 Experiments matrix

N	Bending radius (X_1)	Metal-sheet thickness (X_2)	Gap (X_3)	Length of the fold (X_4)	Y
01	-1	-1	-1	-1	2.7433
02	1	-1	-1	-1	3.1858
03	-1	1	-1	-1	2.5727
04	1	1	-1	-1	2.8683
05	-1	-1	1	-1	3.0503
06	1	-1	1	-1	3.4928
07	-1	1	1	-1	2.8797
08	1	1	1	-1	3.1753
09	-1	-1	-1	1	2.7433
10	1	-1	-1	1	3.1858
11	-1	1	-1	1	2.5727
12	1	1	-1	1	2.8683
13	-1	-1	1	1	3.156
14	1	-1	1	1	3.4685
15	-1	1	1	1	3.0586
16	1	1	1	1	3.2141

4.2 Experiments matrix

When the variation ranges of the factors are different (between them), it is then necessary to carry out a normalization of the values taken by the factors. We convert the initial values by reduced centered values, which mean that it taken the value -1, for the values describing the low limit of each domain of variation; likewise, we give the value +1 to the upper limits. This offers more, important mathematical simplifications for the calculation.

The mathematical generalization of the study of design of experiments is generally done by the use of the matrix approach. Whence, the experience matrix is represented in a square matrix form X of order 2k.

4.3 Calculation of the effects of factors

Each effect (ai) that acts on the behavior of the metal sheet is defined by a factor (xi). In our case, we have four factors, which lead us to find not only four effects, but also other effects that take into account the interaction between the effects of the four factors, without neglecting the effect (a0) which is an average of all the previous factors. In other words, every response (yi) depends on the action of the combined effects (ai). Analytically, the dependence between the response and the effect can only exist when a definite proportionality exists between them. This proportionality is precisely the factor (ai).

This is what leads us to write

$$\boldsymbol{y}_{(\boldsymbol{n},\boldsymbol{1})} = \boldsymbol{x}_{(\boldsymbol{n},\boldsymbol{p})} * \boldsymbol{a}_{(\boldsymbol{p},\boldsymbol{1})} \tag{1}$$

Table 5 The values of the effects of factors (A) and interactions (B)

(A)

Main effects				
Average (a_0)	Bending radius (a_1)	Metal-sheet thickness (a_2)	Gap (a_3)	Length of the fold (a_4)
3.01472	0.167644	-0.11350	0.17219	0.018693

(B)

Interactions					
Ben*Met (I_{12})	Ben*Gap (I_{13})	Ben*Len (I_{14})	Met*Gap (I_{23})	Met*Len (I_{24})	Gap*Len (I_{34})
-0.0373	-0.0168	-0.01688	0.0085	0.00859	0.01869

- $y_{(n,1)}$: The set of responses is transcribed by a colon vector (y) with 2^k elements
- $x_{(n,p)}$: The experience matrix
- $a_{(p,1)}$: The colon vector of all effects of factors and interactions (2^k elements)

The resolution of the Eq. (1) is generally conducted according to the least squares method, and the solution is noted (a).

This solution is given by the following notation taken from the theory of matrix calculation

$$a = {}^{t}(\mathbf{xx})^{-1}.{}^{t}(\mathbf{x}).\mathbf{y} \tag{2}$$

The effects values of the factors as well as the interactions will be as follows:

5. Analysis with a single factor

The figure above shows the four main factors effect as a function of the response. The slopes illustrate the influence of each factor on the response. The largest slopes in absolute value are represented by Figs. 3(a) and (c), which shows that the folding radius and the gap are the most influential factors in the model. The sheet thickness varies inversely with the folding radius (Fig. 3(a)) and the gap (Fig. 3(c)) which shows that their increase causes a decrease in the return elastic. On the other hand, the least sensitive slope is the curve of the fold length effect (Fig. 3(d)) which means that this phenomenon does not depend on this factor.

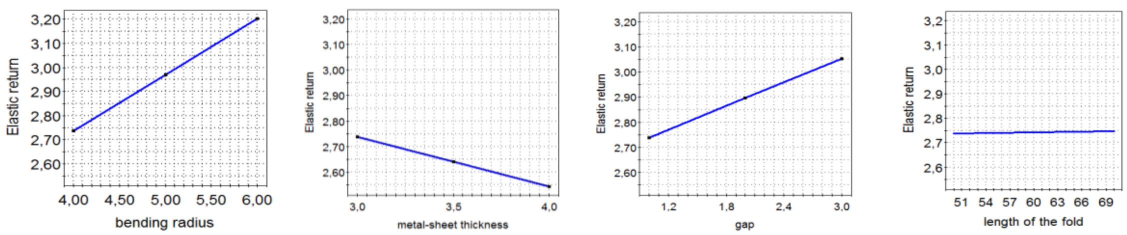

Fig. 3 Representation of the effects of the main factors

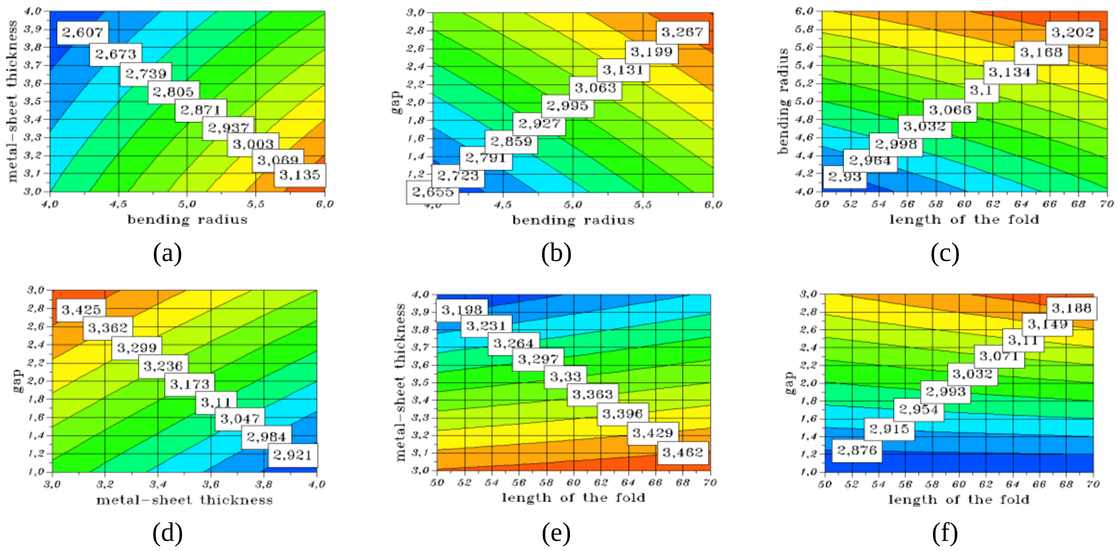

Fig. 4 Representation of interactions

6. Curves ISO-reponses

To analyze the effect of I_{12}, I_{13}, I_{14}, I_{23}, I_{24} and I_{34}, we have to see the effect of the variation of two factors on the response, at the same time, since the interaction is a secondary factor and by definition their variation depends on the variation of the two main factors.

In Figs. 4(a), (b) and (c), which represent the interactions I_{12}, I_{13} and I_{14}, shows that if the folding radius is at its high level, the elastic return increases to high values, as the level of the other factors. The interaction I_{12} I_{23}, I_{24} (Figs. 4(a), (d) and (e)) shows that the values of elastic return are low if the sheet thickness takes very low values. For the interactions I_{14}, I_{34} and I_{24}, the curves Iso-response show that the effect of the fold length is always less influential than the other factors.

7. Conclusions

Despite the advances made at several levels, including experimental (techniques enable to show the elementary characteristics of a material), numerical (calculation codes capable of carrying out complex simulations) and theoretical (performing models of behavior), Nevertheless, much remained to be done before arriving at a perfect mastery of the prediction of certain “unwanted” phenomena related to formatting, such as elastic return.

In this paper, we carried out a numerical study of the shaping of thin metal sheets. This study quantified the effects of the four factors, such as folding radius, thickness of metal sheet, gap and length of the fold, on elastic return. The results obtained are encouraging, this is confirmed according to the file test (chosen model); the use of design of experiments method shows that all the factors have a significant effect and that the gap factor is the most influential parameter.

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