E-ISSN: 2676-6167 | P-ISSN: 2538-5100

Journal of Applied Research on Industrial Engineering

www.journal-aprie.com

J. Appl. Res. Ind. Eng. Vol. 8, No. 3 (2021) 290–308.

Paper Type: Research Paper

Modeling of the Springback in Folding Using the Experimental Design Method

Walid Meslameni[1,*], **Chokri Ben Salem**[2]

[1] Department of Mechanical Engineering, Higher Institute of Technological Studies of Sfax, ISET de Sfax, Tunisia; meslameni.walid@gmail.com.

[2] Department of Mechanical Engineering, Higher Institute of Technological Studies of Sfax, ISET de Sfax, Tunisia; bensalem.chokri@yahoo.fr.

Citation:

Meslameni, W., & Ben Salem, C. (2021). Modeling of the springback in folding using the experimental design method. *Journal of applied research on industrial engineering, 8*(3), 290-308.

Received: 08/04/2021 Reviewed: 02/06/2021 Revised: 20/06/2021 Accepted: 03/07/2021

Abstract

Bending is one of the most frequently used processes in the sheet metal products industry. The major users are mainly the automotive, aeronautics and electrical engineering industries. It is necessarily a cold forming operation of a flat material, with or without lubricant, obtained notably by exceeding its elastic limit. After retraction of the tools and relaxation of the stresses, a springback consequently occurs and a permanent deformation persists causing certain geometric modifications of the product. As a matter of fact, this phenomenon, will absolutely affect the angle and curvature of the bend, for such reason it must be taken into consideration in order to manufacture sheet metal parts bent within acceptable tolerance limits. However, the value of this springback is influenced by a multiplicity of process parameters, such as the thickness of the sheet, the hold time of the bending operation, the material properties and last but not least the depth of strike of the tool. In this paper, we have developed a model for predicting springback in the air V-bending process using the design of experiments method. Four three-level factors were considered in order to model springback in using the Response Surface Method (RSM). The experimental tests were carefully carried out on a HACO press brake and on aluminum, ordinary steel and stainless steel specimens with different thicknesses. The in-depth study of the response surfaces to the different tests with the method of analysis of variance (ANOVA), allowed us to determine a robust empirical model linking the springback to the variables of the study. In addition, several relevant numerical simulations using the Finite Element Method (FEM) with software (Abaqus) were performed to predict the evolution of springback when varying the parameters in the field of design of experiments. In fact, the comparison of the values predicted by the two approaches shows a satisfactory agreement.

Keywords: Air V-bending, Springback, Time keep punch, Depth of bending, Sheet thickness.

1 | Introduction

Initially, the shaping of sheets by folding on industrial presses into finished products is of great importance in the field of mechanical construction. In the same fashion, in the industrial field the development of the folding operation is still carried out by a method based on multiple testing, which makes the operation sometimes long and very high-priced. At this instant, the precise prediction of the springback during bending is therefore imperative for a valuable design of the tooling and of the part to be bent with high geometric quality and a relatively low part scrap.

In the long run, a certain number of researchers have attempted to obtain a basic understanding of the springback behavior of the folding process by using analytical, numerical and experimental modeling methods.

Corresponding Author: meslameni.walid@gmail.com

10.22105/JARIE.2021.280059.1284

We note, in particular, the Gardiner model [1] and [2] and the simplified model of Hasford and Cadell [3] dealing with the taking into account of geometric data and material properties data, an approach of elementary type. Equally important, this type of approach allows, through the use of simple analytical equations, to provide specifically a first estimate of the springback. Chiefly, the works carried out by Queener [4] and Hasford and Cadell by the developed model [3]-[5] consist mainly in the analysis of the capacities of different hardening models to re-transcribe the behavior of the sheets in bending, a second close estimate of the springback with a developed approach. Most of the analytical models are validated by numerical modelizations by the Finite Element Method (FEM) [6], [7] and [8]. Several techniques based on experimental designs are used in different fields, process [9], planning [10], optimization [11], monitoring [12] and modeling techniques with the methodology of experimental designs [13] such as Taguchi [1]-[14], response surfaces [15] or the artificial neural network method [16] are studied. The majority of empirical methods based mainly on practical tests are also validated by numerical models FEM [15]-[17]. Indeed, many valuable questions arise, in particular with regard to the influence of a certain number of factors on the springback in V-bending. Thus, the work carried out by [2]-[18] consists in significantly studying the effect of the type of materials on the springback. With this intention, the same work is carried out by taking into account the effect of the different thicknesses of the sheet by the work of [2]-[19], also to analyze the impact of the effect of the charge holding time [20], the descent of the punch [1] and the variation of the temperature [21].

In the light of several works which have been carried out in this direction. Let us cite in particular Aerens et al. [22] who studied the influence of three types of sheet material, steel, austenitic stainless steel and aluminum subjected to bending using the elasticity modulus. We will cite the work of Karaagaç [20] the evaluation of the parameters of V-bending on the springback using the flexforming process to study the effect of the load holding time, he set out to define by practical studies the most important parameters that affect the springback. With attention to other authors who have been more interested to the influence of the sheet thickness on the prediction of springback as did Miranda et al. [23] a variation of 1 to 6 mm. It is worth noting that mention may also be made of studies on the value of the descent of the punch during the folding operation, which take into account a practical incremental folding methodology to control uniquely the movement of the punch as proposed by Wang et al. [3].

All the models used in folding must imperatively be associated with practical and numerical tests sufficiently precise to make them robust. Indeed, if the error made on the estimate of springback in simulation is too large, then all these models risk diverging or else converging towards a notably false optimum.

Overall, the objective of the work reported in this article is therefore to take stock on the influence of the bending parameters in order to model the elastic behavior on the springback with the method of experimental designs and the FEM.

2 | Principle of Springback

In the first place, the folding of the sheets as a process is a cold forming operation obtained by exceeding the elastic limit of the sheet. Then, after the punch has receded and the stresses have been relaxed, an imminent spring back occurs, permanent deformation persists expressively and the dimensions are out of tolerance.

Indeed, the springback *(r)* comes in several forms such as the difference between the angle before the withdrawal of the punch *(a_i)* and the angle after the release of the sheet *(a_f)* as it is definitely indicated in *Fig. 1*.

$$r=\alpha_f-\alpha_i. \quad (1)$$

On the one hand, by a ratio of the radii of curvature before the withdrawal of the punch *(R_i)* and the angle after the relaxation of the sheet *(R_f)* expressed by the simplified model of Hasford and Cadell [3] which is given by *Eq. (2).*

$$r=\frac{1}{R_i}-\frac{1}{R_f}=\frac{2\sqrt{3}\sigma_e(1-\nu^2)}{t\times E}. \tag{2}$$

$$r=\frac{1}{R_i}-\frac{1}{R_f}=\frac{6\,K'(1-\nu^2)}{(n+2)\;t\times E}\times\left(\frac{t}{2R_i}\right)^n. \tag{3}$$

On the other hand, by the developed model of Hasford and Cadell [3]-[5] using *Eq. (3).*

Alternatively, by the Gardiner model which is the most used in the calculation of the springback [1]-[2] it is exactly given by *Eq. (4).*

$$r=\frac{R_i}{R_f}=4\left(\frac{R_i\;\sigma_e}{E\;t}\right)^3-3\left(\frac{R_i\;\sigma_e}{E\;t}\right)+1. \tag{4}$$

Otherwise, by the Queener model [4] which is defined by *Eq. (5).*

$$r=\frac{R_i}{R_f}=1-\frac{3\;K(1-\nu^2)}{(2+n)E\left(\frac{3}{4}\right)^{\frac{1+n}{2}}}\left(\frac{2R_i}{t}\right)^{1-n}. \tag{5}$$

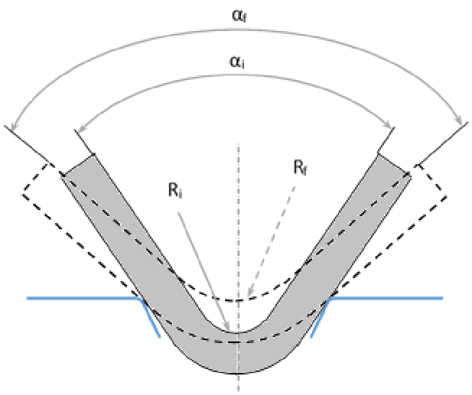


Fig. 1. The angles before and after removing the punch.

3 | Materials and Experiences

By all means, the tests are carried out on aluminum (1050A H12), hot-rolled Steel (S235) and austenitic stainless steel (AISI 304L) specimens, cut in the form of a rectangle of length L = 100 mm and width l = 20 mm at thicknesses 1mm, 1.5mm and 2mm wide with the laser along the rolling direction. Important to realize that the test specimens are folded on the (HACO PPM 2060) programmable hydraulic press brake.

The punch and the die are V-shaped, with characteristics:

- *Punch angle: α_p = 86°; spout radius: r = 1.5 mm.*
- *Matrix angle: α_m = 86°; opening: w = 24 mm.*

In this case, the angle under load was measured using a simple arrangement with two gauge blocks of the same size as fairly shown in the *Fig. 2* with:

$$\alpha_i = 180° - 2\beta_i. \tag{6}$$

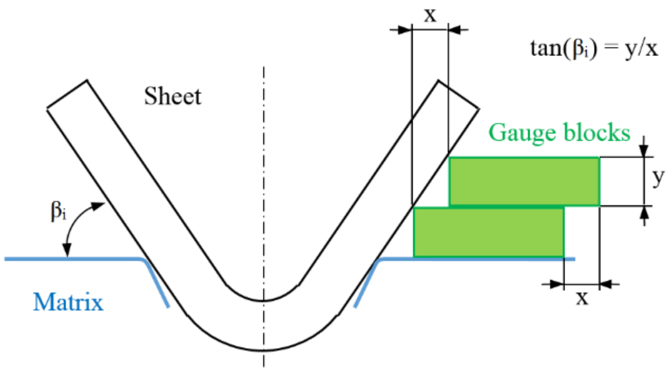


Fig. 2. The initial angle α_i during loading.

At the end of each bending test, the angle formed by the test piece after springback *(α_f)* is obviously measured by a profile projector (PJ-A3000) with an accuracy of ± 0.01 degrees *Fig. 3*.

Fig. 3. Profile projector PJ-A3000.

The range of variation of the folding parameters are:

- *The time (T) varies between 2 min and 14 min.*
- *The striking depth (P) varies between 7 mm and 3 mm.*
- *The thickness (Ep) varies from 1mm to 2 mm.*
- *The materials of the sheet to be bent (M) are defined in Table 1 and Table 2.*

Table 1. Mechanical properties of the sheets used.

Materials M		Young's Modulus (GPa)	Poisson's Ratio	Volumic mass (kg.m^{-3})	Yield Strength (MPa)	Tensile Strength (MPa)
1	Aluminum 1050A	69	0.33	2700	65	110
2	Steel S235	210	0.28	7800	235	340
3	Stainless steel AISI 304L	200	0.29	7900	310	620

Table 2. Chemical composition of materials.

Aluminum	Si%	Fe%	Cu%	Mn%	Mg%	Zn%	Ti%	Al%
1050A	0.25	0.4	0.05	0.05	0.05	0.07	0.05	99.5
Steel S235	C%	Mn%	Si%	P%	S%	N%	Cu%	
hot rolled	0.17	1.4	-	0.04	0.04	0.012	0.55	
Stainless steel	C%	Si%	Mn%	P%	S%	Cr%	Ni%	N%
AISI 304L	0.03	1	2	0.045	0.015	19.5	10	0.11

Given the diversity of the folding parameters for each level as indicated on *Table 3* and in order to have a simple modeling, it is critically necessary to assign, according to the standardization of the experimental designs for each parameter, reduced centered values *(-1; 0; 1)*. Therefore, this modeling will ultimately offer a simple mathematical representation and therefore a much more significant development of the empirical model.

Table 3. Matrix levels.

Settings		Level 1	Level 2	Level 3
X1	Time [T] (min)	2	8	14
X2	Depth [P] (mm)	7	5	3
X3	Thickness [Ep] (mm)	1	1.5	2
X4	Material [M]	Aluminum 1050A	Steel S235	Stainless steel AISI 304L

What is more, the experiments carried out are summarized in the form of a matrix of experiments. Most compelling evidence is shown in complete plan the number of possible combinations between all the levels is *(3^4)* or *(81)* experiments *Table 4*.

Table 4. Plan and experimental results of the tests carried out.

N° Exp	Factors				Response	
	Time (min)	Depth (mm)	Thickness (mm)	Material	r (°)	Final angle (°)
1	2	7	1	1050A	2.43	113.94
2	8	7	1	1050A	2.80	114.13
3	14	7	1	1050A	2.83	114.83
4	2	5	1	1050A	3.03	132.09
5	8	5	1	1050A	2.61	131.80
6	14	5	1	1050A	2.94	132.22
7	2	3	1	1050A	2.60	150.14
8	8	3	1	1050A	2.55	149.78
9	14	3	1	1050A	3.12	149.93
10	2	7	1.5	1050A	2.20	109.40
11	8	7	1.5	1050A	2.61	109.55
12	14	7	1.5	1050A	2.37	109.55
13	2	5	1.5	1050A	2.24	126.55
14	8	5	1.5	1050A	2.02	126.32
15	14	5	1.5	1050A	2.54	126.58
16	2	3	1.5	1050A	2.51	145.31
17	8	3	1.5	1050A	2.13	144.91
18	14	3	1.5	1050A	1.39	144.28
19	2	7	2	1050A	1.60	102.95
20	8	7	2	1050A	1.47	102.52
21	14	7	2	1050A	1.64	102.69
22	2	5	2	1050A	1.19	119.73
23	8	5	2	1050A	1.95	119.80
24	14	5	2	1050A	1.58	120.14
25	2	3	2	1050A	1.22	137.95
26	8	3	2	1050A	1.32	137.57
27	14	3	2	1050A	1.62	139.23
28	2	7	1	S235	2.89	112.71
29	8	7	1	S235	2.78	111.86
30	14	7	1	S235	2.74	110.92
31	2	5	1	S235	2.43	129.91
32	8	5	1	S235	2.65	129.38
33	14	5	1	S235	3.09	129.81
34	2	3	1	S235	2.30	149.03
35	8	3	1	S235	2.18	148.67
36	14	3	1	S235	2.82	149.06
37	2	7	1.5	S235	1.86	105.66
38	8	7	1.5	S235	1.68	105.21
39	14	7	1.5	S235	1.87	105.06

Meslameni and Ben Salem | J. Appl. Res. Ind. Eng. 8(3) (2021) 290-308

Table 4. (Continuted).

N° Exp	Factors Time (min)	Response Depth (mm)	N° Exp	Factors Time (min)	Response Depth (mm)	N° Exp
40	2	5	1.5	S235	1.80	123.54
41	8	5	1.5	S235	1.94	123.21
42	14	5	1.5	S235	1.90	123.57
43	2	3	1.5	S235	1.63	142.00
44	8	3	1.5	S235	1.20	141.75
45	14	3	1.5	S235	1.54	141.42
46	2	7	2	S235	2.55	102.44
47	8	7	2	S235	1.28	101.53
48	14	7	2	S235	2.68	101.75
49	2	5	2	S235	1.39	118.98
50	8	5	2	S235	1.97	119.21
51	14	5	2	S235	1.99	119.59
52	2	3	2	S235	1.27	138.48
53	8	3	2	S235	1.64	138.42
54	14	3	2	S235	1.56	138.41
55	2	7	1	AISI 304L	8.04	111.98
56	8	7	1	AISI 304L	8.25	112.81
57	14	7	1	AISI 304L	8.39	113.97
58	2	5	1	AISI 304L	6.87	131.28
59	8	5	1	AISI 304L	5.73	128.96
60	14	5	1	AISI 304L	6.67	131.98
61	2	3	1	AISI 304L	5.71	150.82
62	8	3	1	AISI 304L	5.19	149.69
63	14	3	1	AISI 304L	6.29	150.13
64	2	7	1.5	AISI 304L	5.03	106.32
65	8	7	1.5	AISI 304L	4.71	106.72
66	14	7	1.5	AISI 304L	4.78	104.56
67	2	5	1.5	AISI 304L	4.43	122.55
68	8	5	1.5	AISI 304L	3.71	124.41
69	14	5	1.5	AISI 304L	4.26	124.31
70	2	3	1.5	AISI 304L	3.46	141.61
71	8	3	1.5	AISI 304L	3.19	141.26
72	14	3	1.5	AISI 304L	3.62	141.68
73	2	7	2	AISI 304L	4.01	100.01
74	8	7	2	AISI 304L	4.27	100.21
75	14	7	2	AISI 304L	4.39	99.64
76	2	5	2	AISI 304L	3.75	117.44
77	8	5	2	AISI 304L	3.15	118.46
78	14	5	2	AISI 304L	3.58	118.55
79	2	3	2	AISI 304L	2.36	137.70
80	8	3	2	AISI 304L	2.50	137.58
81	14	3	2	AISI 304L	2.63	137.84

A classical polynomial model of order two carries out the springback prediction. This model takes into account the effects of factors and these interactions, is given explicitly by:

$$r = b0 + b1*X1 + b2*X2 + b3*X3 + b4*X4 + b11(X1)^2 + b22(X2)^2 + b33(X3)^2 + b44(X4)^2 + b12(X1*X2) + b13(X1*X3) + b23(X2*X3) + b14(X1*X4) + b24(X2*X4) + b34(X3*X4). \quad (7)$$

With:

$X1 = T; X2 = P; X3 = Ep; X4 = M.$

To emphasize, the complete classical experimental design allows us markedly to estimate the 15 unknown parameters of the model:

I. b0: The average.
II. bi: The effects of (Xi) factors of order 1.
III. bii: The effects of (Xi) factors of order 2.

IV. bij: The effects of interactions between the factors (Xi) and (Xj).

Another key point, four major factors with three levels were specifically considered in order to obtain an empirical model to predict spring back by using the well- known Response Surface Method (RSM). Notably, interactions of order equal to or greater than three are chiefly neglected. Correspondingly, to carry out this study and the statistical analysis, it is quietly essential to carry out repetitions of tests. As an illustration, in our case we carried out 3 repetitions or *(243)* experiments *Fig. 4*.

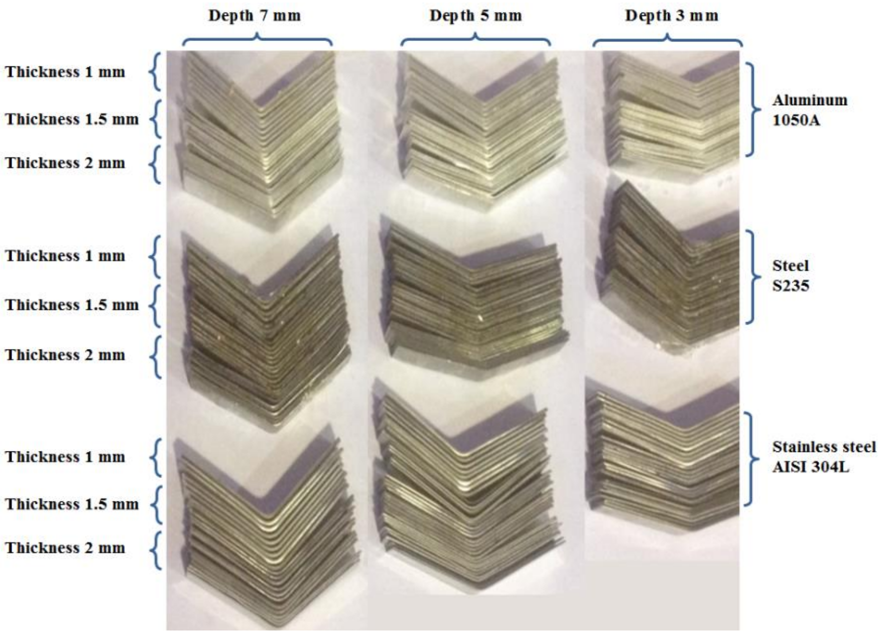


Fig. 4. Specimens of the 243 experiments.

4 | Results and Discussion

The springback is particularly measured as a difference between the angle (a_i) during the loading of the punch and the angle (a_f) after the sheet is released. For each test, the results of the springback obtained for the factors: holding time *(T)*, depth *(P)*, thickness *(Ep)* and sheet material *(M)* are shown in *Fig. 5*.

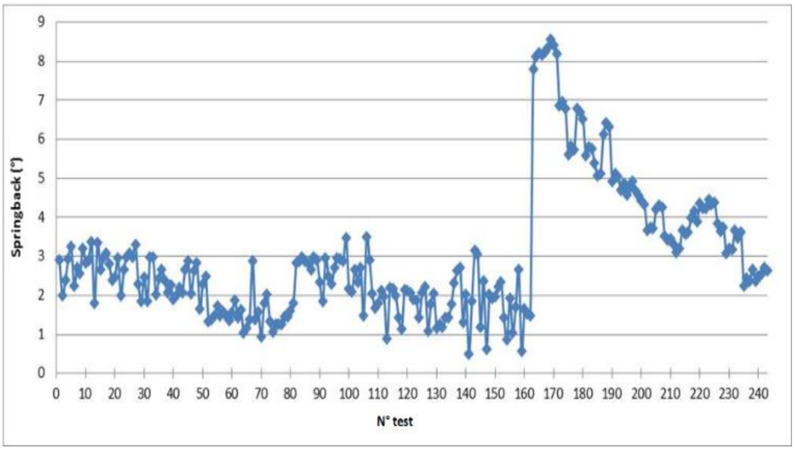


Fig. 5. Experimental results of the 243 trials.

For the purpose of assessing the order of influence of each factor on the springback, we first determine the average of the effects relating to each level, then the highest differences between the levels and their rankings. The factor most influencing the springback is the one with the maximum deviation *Table 5*.

Meslameni and Ben Salem | J. Appl. Res. Ind. Eng. 8(3) (2021) 290-308

Table 5. Ranking of factors.

	T	P	Ep	M
Level 1	2.98	3.41	3.98	2.17
Level 2	2.88	3.02	2.69	2.06
Level 3	3.15	2.58	2.25	4.71
delta	0.27	0.83	1.73	2.65
Rank	4	3	2	1

Fig. 6 it represents the evolution of springback as a function of the average effects relative to each level for the four factors.

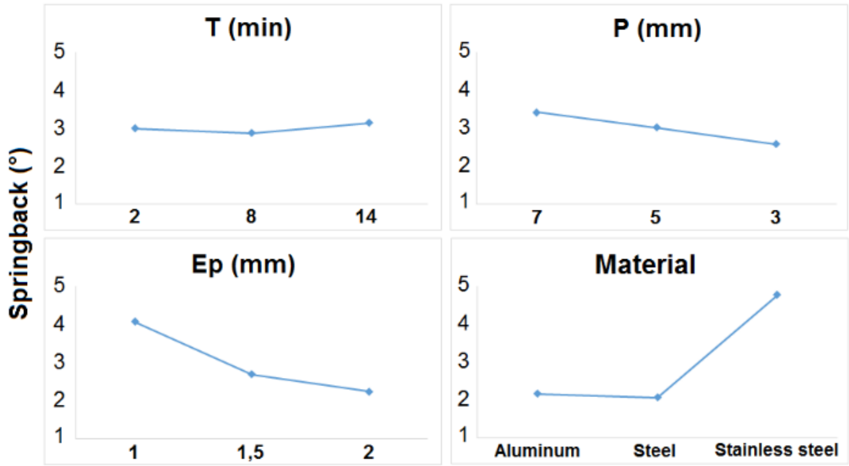


Fig. 6. Curves of mean effects on springback.

With attention to the curves in *Fig. 6*, we can determine that the spring back:

- *Strongly depends on the type of material (M) and obviously the thickness of the sheet (Ep).*
- *Decreases with increasing thickness (Ep).*
- *Proportional to the depth (P).*
- *Does not depend on the holding time (T) of the punch since the curve is practically constant for the three levels.*

However, we notice that the evolution of the springback as a function of the material *(M)* is almost identical for steel and aluminum while, it is strongly increased for stainless steel and reached the value 4.71°.

The coefficients of the effects of the factors *(bi)*, *(bii)* and their interactions *(bij)* are clearly determined and presented in *Table 6*. Additionally, we wish to approach springback in its industrial aspect. And then, the study of response surfaces is mainly associated with the use of polynomials of second order. With attention to, we propose an informative and simplified model, which designate it possible to anticipate springback and its high sensitivity to variations in certain parameters related to folding. Again to see the influence of each of the coefficients *(bi)* and *(bij)* of the model on the spring back we have to check the test (Student) and we adopt the hypothesis *(H0)*-during which we calculate for each coefficient the term *(ti)* using *Eq. (8)*. (see *Table 6*):

$$t_i = \frac{\text{bi}}{\text{Standard Devi. bi}}. \tag{8}$$

Although this may be true, the low values of (ti) indicate the rejection of the hypothesis (H0) and therefore the coefficient related to this term has no influence on the model relied on.

Table 6. Model coefficient estimates and statistics.

Name	bi	Standard Devi.	ti	Signif. %
b0	1.633	0.072	22.75	< 0.01 ***
b1	0.075	0.029	2.54	1.19 *
b2	-0.419	0.029	-14.29	< 0.01 ***
b3	-0.914	0.029	-31.20	< 0.01 ***
b4	1.304	0.029	44.52	< 0.01 ***
b11	0.197	0.051	3.88	0.0151 ***
b22	-0.021	0.051	-0.42	67.4
b33	0.467	0.051	9.20	< 0.01 ***
b44	1.411	0.051	27.80	< 0.01 ***
b12	0.013	0.036	0.37	71.3
b13	-0.007	0.036	-0.18	85.5
b23	0.017	0.036	0.48	63.0
b14	-0.002	0.036	-0.04	96.5
b24	-0.428	0.036	-11.94	< 0.01 ***
b34	-0.533	0.036	-14.86	< 0.01 ***

* Significant value at 95% confidence level
** Significant value at 99% confidence level
*** Significant value at 99.9% confidence level

In the same way it is interesting to note that only the interaction effect between factors 2 and 4 (i.e. between the depth and type of the sheet material) and 3 and 4 (i.e. say between the thickness of the sheet and the type of material) seems to be significantly small and different from zero (and this according to the hypothesis tests carried out in the last column of *Table 6*). Consequently, there does not seem to be a significant interaction effect between the punch holding time and the oth er factors.

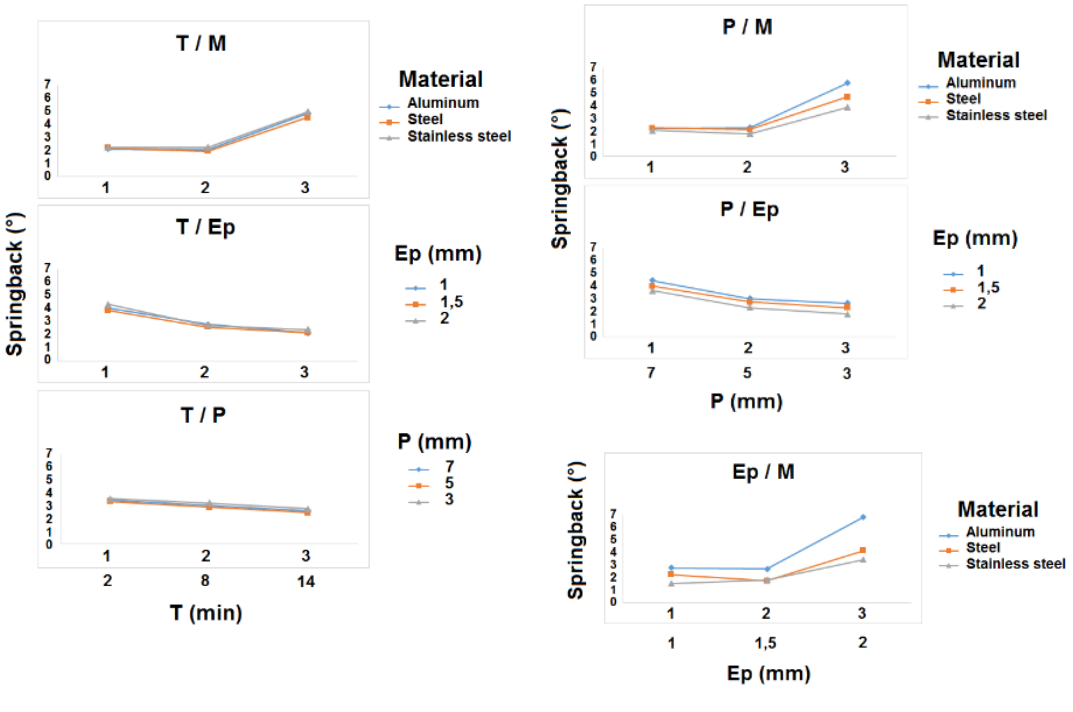


Fig. 7. Curves interaction effects on springback.

Equally important, from the curves of the effects of the interactions of the parameters of *Fig. 7*. It is necessary to perceive that only the effect of the interactions between the depth *(P)* and material *(M) (P / M)* and between the thickness factors *(Ep)* and material *(M) (Ep / M)* appear significant and compelling. Conversely, it turns out that there can be no mutual interaction between time and other factors considering the line segments in the interaction graphs in *Fig. 7* are all parallel.

Together with, the results of the statistical analysis of variance (ANOVA) are valiantly summarized in *Table 7*.

Table 7. Analysis of variance.

Source of variation	SS	DOF	MS	Fisher ratio	Signif.
Regression « R »	612.2196	14	43.7300	314.4979	< 0.01 ***
Residues « E »	76.0036	228	0.3333		
Total « T »	688.2232	242			

With:

$SS_T = SS_R + SS_E$. (9)

$MS_R = SS_R / DOF_R$. (10)

$MS_E = SS_E / DOF_E$. (11)

Initially, Fisher's ratio is first assessed by:

$F. Ratio = MS_R / MS_E$. (12)

Then compared to that given by the Fisher statistical table:

- $F0.05\ (DOF_R;\ DOF_E) = 1.71$.
- $F0.01\ (DOF_R;\ DOF_E) = 2.12$.
- $F\ 0.001\ (DOF_R;\ DOF_E) = 2.64 < 314.4979$.

In essence, Fisher's test therefore makes it possible to highlight the existence of a statistically significant difference at the 99.9% confidence level, hence the appearance of three clear stars in the significance of the regression in *Table 7*.

However, to consolidate the statistical robustness of the model, we determine the multiple linear correlation coefficient *(R2)* we using the following equations.

$R2 = SS_R / SS_T = 1 – (SS_E / SS_T)$. (13)

As it must be between $0 \leq R2 \leq 1$. This coefficient is close to 1 (R2 = 0.890) so the model can be considered of sufficient and acceptable quality.

Table 8. Additional analysis with correlation coefficients.

Response Standard Deviation	0.373
R2	0.890
Number of degrees of freedom	162

Thus, the springback *(r)* as a function of the four parameters: the holding time *(T)*, the depth *(P)*, the thickness *(Ep)* and the material *(M)* is clearly defined by the following equation.

$$r = 1.633 + 0.075 * T - 0.419 * P - 0.914 * Ep + 1.304 * M + 0.197 * t^2 + 0.467 * Ep^2 + 1.411 * M^2 - 0.428 * P * M - 0.533 * Ep * M. \quad (14)$$

In the light of the evolution of the springback predicted by this model for each test is shown in *Fig. 8*.

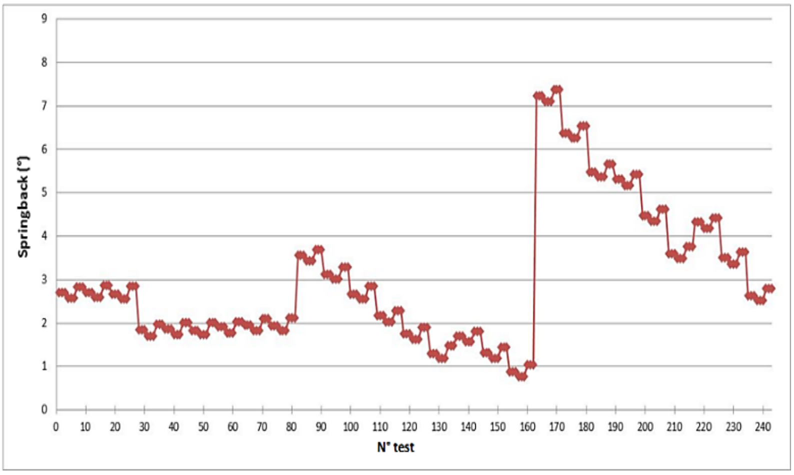


Fig. 8. Evolution of the springback of the model.

In like manner, the results of the springback thus developed by the empirical model are compared with those determined experimentally from the air V-bending tests of sheets of different thicknesses on a press brake (*Fig. 9* and *Table 9*). Equally, the agreement between the two values measured and predicted by this model tells us that the developed model offers us a precise and exact estimate of the springback.

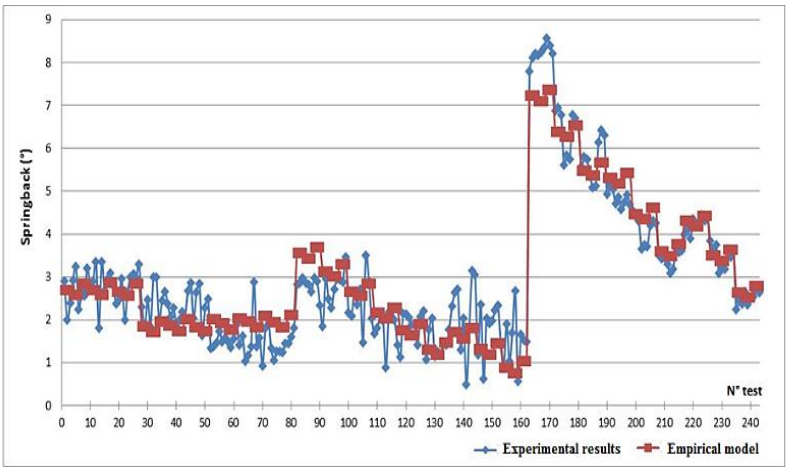


Fig. 9. Comparison of the empirical model with the experimental results.

Table 9. Difference between empirical model and experimental results.

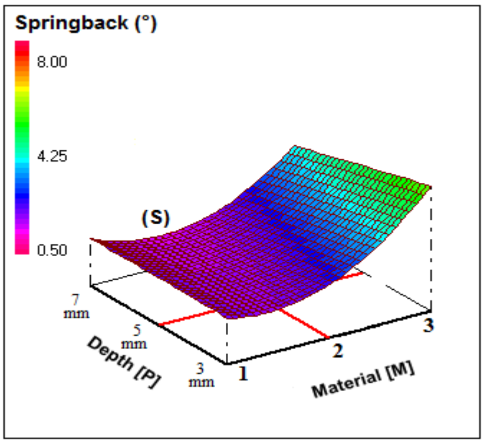
N	Exp.	Calc.	Différence	N°	Exp.	Calc.	Différence	N°	Exp.	Calc.	Différence
1	113.65	114.71	-1.06	**82**	112.36	112.60	-0.24	**163**	111.84	112.46	-0.62
2	114.08	114.71	-0.63	**83**	112.59	112.60	-0.01	**164**	111.84	112.46	-0.62
3	114.10	114.71	-0.61	**84**	113.18	112.60	0.57	**165**	112.26	112.46	-0.20
4	113.77	114.42	-0.65	**85**	112.42	112.35	0.06	**166**	112.76	112.26	0.49
5	114.82	114.42	0.39	**86**	112.34	112.35	-0.01	**167**	112.76	112.26	0.49
6	113.82	114.42	-0.60	**87**	110.82	112.35	-1.53	**168**	112.93	112.26	0.66
7	114.30	114.52	-0.22	**88**	110.62	112.50	-1.88	**169**	114.09	112.45	1.63
8	115.10	114.52	0.57	**89**	110.93	112.50	-1.57	**170**	114.09	112.45	1.63
9	115.10	114.52	0.57	**90**	111.21	112.50	-1.29	**171**	113.73	112.45	1.27
10	131.76	132.03	-0.27	**91**	130.60	130.27	0.32	**172**	131.31	130.48	0.82
11	132.26	132.03	0.22	**92**	130.70	130.27	0.42	**173**	131.31	130.48	0.82
12	132.26	132.03	0.22	**93**	128.44	130.27	-1.83	**174**	131.22	130.48	0.73
13	130.52	131.77	-1.25	**94**	129.39	130.06	-0.67	**175**	128.92	130.31	-1.39
14	132.44	131.77	0.66	**95**	129.80	130.06	-0.26	**176**	128.92	130.31	-1.39
15	132.44	131.77	0.66	**96**	128.97	130.06	-1.09	**177**	129.04	130.31	-1.27
16	131.77	131.92	-0.15	**97**	129.65	130.25	-0.60	**178**	132.07	130.54	1.52
17	132.45	131.92	0.52	**98**	130.00	130.25	-0.25	**179**	132.07	130.54	1.52
18	132.45	131.92	0.52	**99**	129.80	130.25	-0.45	**180**	131.81	130.54	1.26
19	150.36	150.34	0.01	**100**	148.88	148.92	-0.04	**181**	150.77	149.48	1.28
20	150.03	150.34	-0.31	**101**	149.19	148.92	0.26	**182**	150.77	149.48	1.28

Meslameni and Ben Salem | J. Appl. Res. Ind. Eng. 8(3) (2021) 290-308

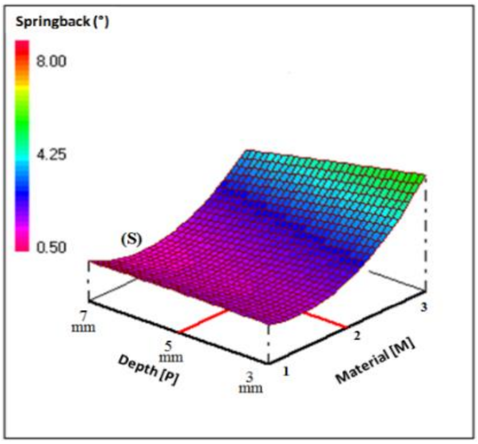
Table 9. (Continuted).

N	Exp.	Calc.	Différence	N°	Exp.	Calc.	Différence	N°	Exp.	Calc.	Différence
21	150.03	150.34	-0.31	**102**	149.03	148.92	0.10	**183**	150.94	149.48	1.45
22	149.52	150.12	-0.60	**103**	148.52	148.75	-0.23	**184**	149.78	149.35	0.42
23	149.91	150.12	-0.21	**104**	149.19	148.75	0.43	**185**	149.78	149.35	0.42
24	149.91	150.12	-0.21	**105**	148.31	148.75	-0.44	**186**	149.52	149.35	0.16
25	149.47	150.30	-0.83	**106**	149.55	148.98	0.56	**187**	150.07	149.62	0.44
26	150.17	150.30	-0.13	**107**	149.22	148.98	0.23	**188**	150.07	149.62	0.44
27	150.17	150.30	-0.13	**108**	148.43	148.98	-0.55	**189**	150.25	149.62	0.62
28	109.59	108.45	1.13	**109**	105.74	106.13	-0.39	**190**	106.29	105.77	0.52
29	109.31	108.45	0.85	**110**	105.79	106.13	-0.34	**191**	106.29	105.77	0.52
30	109.31	108.45	0.85	**111**	105.46	106.13	-0.67	**192**	106.40	105.77	0.63
31	109.31	108.19	1.11	**112**	105.37	105.91	-0.54	**193**	106.76	105.59	1.16
32	109.67	108.19	1.47	**113**	105.27	105.91	-0.64	**194**	106.76	105.59	1.16
33	109.67	108.19	1.47	**114**	104.99	105.91	-0.92	**195**	106.64	105.59	1.04
34	109.67	108.33	1.33	**115**	104.99	106.09	-1.10	**196**	104.58	105.82	-1.24
35	109.49	108.33	1.15	**116**	105.61	106.09	-0.48	**197**	104.58	105.82	-1.24
36	109.49	108.33	1.15	**117**	104.58	106.09	-1.51	**198**	104.52	105.82	-1.30
37	126.36	125.75	0.60	**118**	123.00	123.77	-0.77	**199**	122.63	123.76	-1.13
38	126.65	125.75	0.89	**119**	124.82	123.77	1.04	**200**	122.63	123.76	-1.13
39	126.65	125.75	0.89	**120**	122.82	123.77	-0.95	**201**	122.41	123.76	-1.35
40	126.50	125.53	0.96	**121**	124.09	123.59	0.49	**202**	124.40	123.63	0.77
41	126.24	125.53	0.70	**122**	122.72	123.59	-0.87	**203**	124.40	123.63	0.77
42	126.24	125.53	0.70	**123**	122.84	123.59	-0.75	**204**	124.45	123.63	0.82
43	126.46	125.71	0.74	**124**	123.05	123.81	-0.76	**205**	124.29	123.89	0.39
44	126.64	125.71	0.92	**125**	124.38	123.81	0.56	**206**	124.29	123.89	0.39
45	126.64	125.71	0.92	**126**	123.29	123.81	-0.52	**207**	124.35	123.89	0.45
46	145.23	144.04	1.18	**127**	141.88	142.41	-0.53	**208**	141.63	142.75	-1.12
47	145.36	144.04	1.31	**128**	142.18	142.41	-0.23	**209**	141.63	142.75	-1.12
48	145.36	144.04	1.31	**129**	141.94	142.41	-0.47	**210**	141.57	142.75	-1.18
49	144.91	143.86	1.04	**130**	141.62	142.27	-0.65	**211**	141.30	142.65	-1.35
50	144.91	143.86	1.04	**131**	141.83	142.27	-0.44	**212**	141.30	142.65	-1.35
51	144.91	143.86	1.04	**132**	141.82	142.27	-0.45	**213**	141.20	142.65	-1.45
52	144.18	144.07	0.10	**133**	141.12	142.53	-1.41	**214**	141.70	142.95	-1.25
53	144.33	144.07	0.25	**134**	141.70	142.53	-0.83	**215**	141.70	142.95	-1.25
54	144.33	144.07	0.25	**135**	141.45	142.53	-1.08	**216**	141.65	142.95	-1.30
55	103.01	103.53	-0.52	**136**	101.96	100.98	0.97	**217**	100.05	100.40	-0.35
56	102.92	103.53	-0.61	**137**	102.48	100.98	1.49	**218**	100.05	100.40	-0.35
57	102.92	103.53	-0.61	**138**	102.90	100.98	1.91	**219**	99.95	100.40	-0.45
58	102.66	103.30	-0.64	**139**	102.03	100.80	1.22	**220**	100.25	100.26	-0.01
59	102.45	103.30	-0.85	**140**	101.53	100.80	0.72	**221**	100.25	100.26	-0.01
60	102.45	103.30	-0.85	**141**	101.04	100.80	0.23	**222**	100.14	100.26	-0.12
61	103.27	103.47	-0.20	**142**	101.40	101.01	0.38	**223**	99.66	100.52	-0.86
62	102.40	103.47	-1.07	**143**	101.89	101.01	0.87	**224**	99.66	100.52	-0.86
63	102.40	103.47	-1.07	**144**	101.98	101.01	0.96	**225**	99.60	100.52	-0.92
64	119.70	120.81	-1.11	**145**	118.74	118.61	0.12	**226**	117.47	118.38	-0.91
65	119.75	120.81	-1.06	**146**	119.95	118.61	1.33	**227**	117.47	118.38	-0.91
66	119.75	120.81	-1.06	**147**	118.25	118.61	-0.36	**228**	117.38	118.38	-1.00
67	120.08	120.62	-0.54	**148**	119.56	118.46	1.09	**229**	118.43	118.28	0.14
68	119.66	120.62	-0.96	**149**	119.43	118.46	0.96	**230**	118.43	118.28	0.14
69	119.66	120.62	-0.96	**150**	118.66	118.46	0.19	**231**	118.53	118.28	0.24
70	119.04	120.83	-1.79	**151**	118.94	118.72	0.21	**232**	118.57	118.58	-0.01
71	120.69	120.83	-0.14	**152**	120.10	118.72	1.37	**233**	118.57	118.58	-0.01
72	120.69	120.83	-0.14	**153**	119.74	118.72	1.01	**234**	118.53	118.58	-0.05
73	138.56	139.08	-0.52	**154**	138.59	137.23	1.35	**235**	137.66	137.35	0.30
74	137.65	139.08	-1.43	**155**	138.63	137.23	1.39	**236**	137.66	137.35	0.30
75	137.65	139.08	-1.43	**156**	138.23	137.23	0.99	**237**	137.78	137.35	0.42
76	138.60	138.93	-0.33	**157**	138.59	137.12	1.46	**238**	137.64	137.28	0.35
77	137.06	138.93	-1.87	**158**	138.86	137.12	1.73	**239**	137.64	137.28	0.35
78	137.06	138.93	-1.87	**159**	137.82	137.12	0.69	**240**	137.47	137.28	0.18
79	138.31	139.18	-0.87	**160**	138.25	137.42	0.83	**241**	137.81	137.62	0.18
80	139.69	139.18	0.50	**161**	138.40	137.42	0.98	**242**	137.81	137.62	0.18
81	139.69	139.18	0.50	**162**	138.59	137.42	1.17	**243**	137.91	137.62	0.28

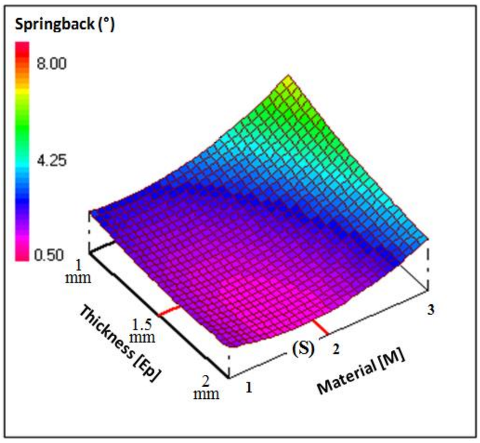
To express differently and for more illustrations to the influence of the significant factors, we set the thickness factor at *Ep=1.5* mm and the time factor at *T=2* min, 8 min and 14 min (*Figs. 10.a, 10.b*, and *10.c*) and we let us trace the response surfaces represented in the material plane *(M)* and the depth *(P)*. After all, we find that the factor *(T)* has no influence on the spring back.



a.



b.



c.

Fig. 10. Variation of springback in the Material (M) and Depth (P) plane: a. for fixed factors, b. for fixed factors, c. for fixed factors: a. T= 2 min; Ep=1.5 mm; b. T= 8 min; Ep=1.5 mm; c. T= 14 min; Ep=1.5 mm.

Meslameni and Ben Salem | J. Appl. Res. Ind. Eng. 8(3) (2021) 290-308

Fig. 11 it fairly allows us to locate the optimum of the value of the springback, the location of the real optimum and that of the stationary point *(S)* which symbolizes a considerate estimator of the position of the optimum initially sought. However, the approximate position of the optimal experimental domain which is mainly sought to minimize the springback of the stationary point is eventually evaluated for the values *M = 2* (Steel) and *Ep = 2* mm.

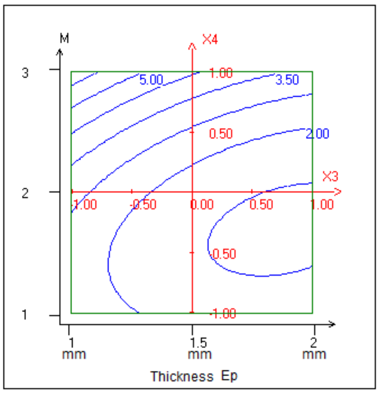


Fig. 11. Variation of the springback in the plane Material (M) and Thickness (Ep)

for fixed factors T = 8 min; P = 5 mm.

Add to this, according to the graphic representation of the variation of the spring back in the plane (Ep) and (P), we deduce in an approximate way the position of the optimal experimental domain sought. Provided that this position main role is to minimize the springback of the stationary point which is estimated for Ep = 2 mm and P = 3 mm.

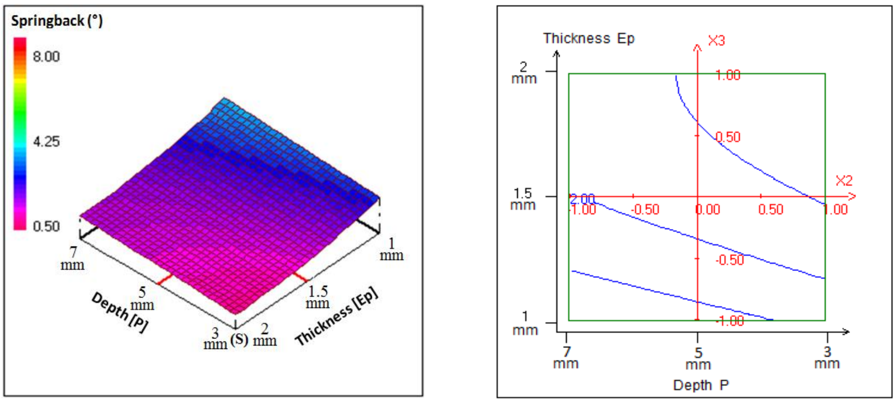


Fig. 12. Variation of the springback in the plane (Ep) and (P) for the fixed factors T = 8 min; M = 2.

5 | Validation of Empirical Modeling by Numerical Simulation FEM

5.1 | Numerical Modeling

We will model numerically by simulating the air v-bending procedure with the finite element calculation software (Abaqus). As the boundary conditions applied to the different simulation elements are the following:

– *For each rigid body we choose reference points as they are indicated in Fig. 13, however we apply an embedding at the reference point of the matrix and a displacement which is represented by the descent and the rise of the reference point of the punch.*

– *The sheet remains free because it is not subject to any conditions. It is positioned symmetrically with the tool. To be sure, the origin of the coordinate system is located in the middle of the sheet and at the bottom line level of the defined mesh.*

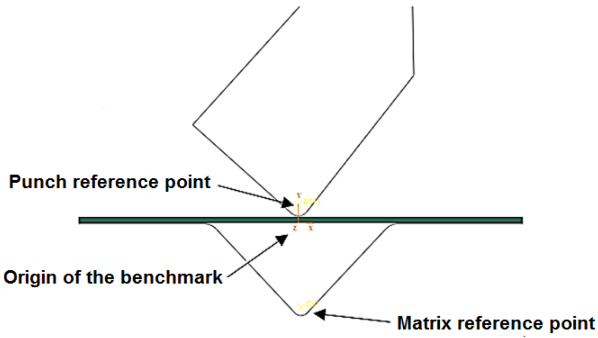
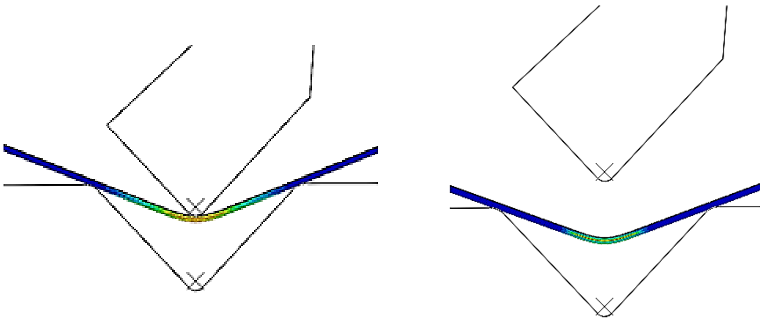


Fig. 13. Representation of the assembly.

Comparatively, the coefficient of friction impacts particularly in the execution of the simulation procedure. However, the value used in our simulation is that of (Steel / Steel) of value $f = 0.1$.

Indeed, we consider that the punch and the matrix of rigid bodies which do not undergo any deformation during bending. Last but not least, the study of the constraints specifies a concentration in the middle of the sheets used, which brings us back to choosing a (Bias) mesh. The result of the simulation is obviously presented in *Fig. 14*.



a. **b.**

Fig. 14. Simulation results: a. simulation of folding during the descent of the punch, b. Simulation of springback after recoil of the punch.

We chose to determine the displacements of all the nodes located at the upper line through the coordinates of the points before the withdrawal of the punch and after the springback.

These displacements are recorded then processed to determine the bending angles, the radius of curvature and the springback for the bending of a sheet of thickness 1 mm in steel (S235) and for an opening of the die w = 24 mm are summarized in *Table 9*.

Table 9. Springback of a sheet of 1 mm for a matrix of width w = 24 mm.

P (mm)	R_i (mm)	R_f (mm)	α_i (°)	α_f (°)	r (°)
3	7.019	7.254	148.23	150.51	2.28
3.5	6.201	6.392	144.30	146.56	2.26
4	5.585	5.745	139.63	141.86	2.22
4.5	5.077	5.213	134.28	136.45	2.17
5	4.660	4.778	130.26	132.37	2.10
5.5	4.317	4.422	126.59	128.62	2.03
6	4.177	4.274	122.78	124.83	1.96
6.5	3.896	3.982	119.58	121.55	1.90
7	3.647	3.724	116.75	118.62	1.83

Fig. 15 it shows the evolution of the springback as a major function of the depth for an opening of the matrix *w = 24 mm* at a variety of thicknesses. Henceforth, all these curves have the same appearance for the different values of sheet thickness, note that the springback varies between 0.56 and 2.26 degrees.

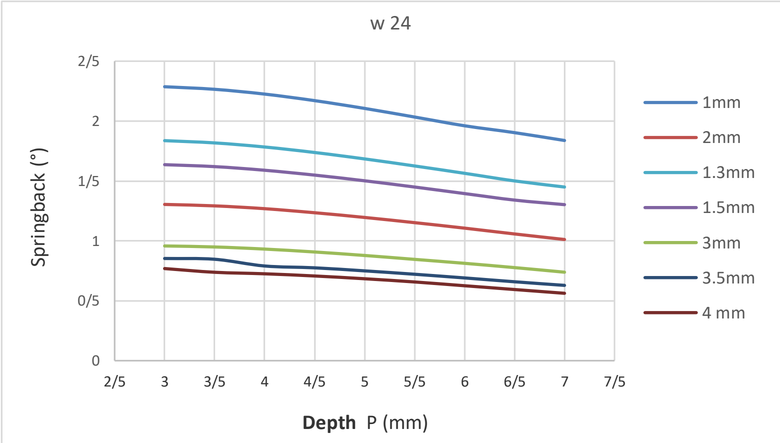


Fig. 15. Evolution of springback as a function of depth for w = 24 mm.

Fig. 16 it represents the evolution of the springback as a function of the thickness of the sheet for depths between 3 and 7 mm. However, we note that the spring back decreases with the increase in the thickness of the sheet ready for bending and increases slightly with the decrease with the descent of the punch.

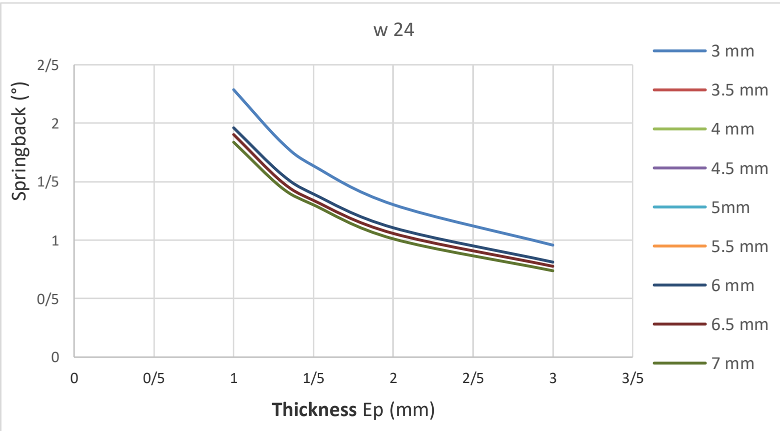


Fig. 16. Evolution of the springback as a function of the thickness for w = 24 mm.

5.2 | Validation of Results

Given these points, we carried out a series of validation measurements of springback on (S235) Steel specimens, the measured angles are compared with those obtained by numerical simulation for the thicknesses of 1 and 2 mm.

Fig. 17 and *Fig. 18* represent the evolution of the final angle after springback, determined by numerical simulation as a function of the depth of the descent of the punch compared with those which are already recorded experimentally.

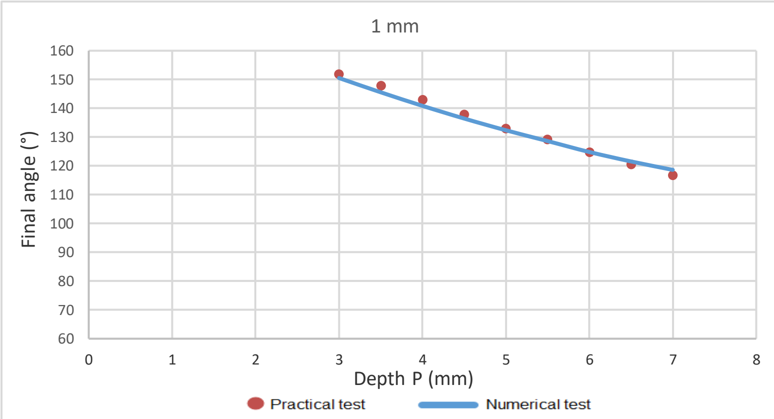


Fig. 17. Confrontation of practical and numerical tests for Ep = 1 mm.

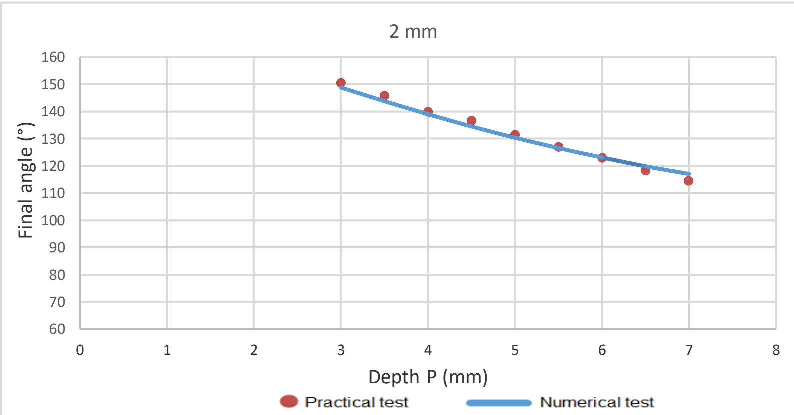


Fig. 18. Confrontation of practical and numerical tests for Ep = 2 mm.

As can be seen, the agreement between the final angles after springback measured and estimated by numerical and satisfactory simulation, the maximum relative difference is 1.07 % for sheets of thickness 1 mm and 0.85 % for thickness 2 mm.

6 | Conclusion

All in all, the objective of this study is to predict the springback during the air V-bending of sheets by experimental modeling with the method of experimental designs in an empirical way.

In this work, we studied, the effects of the parameters of the V-bending of the sheets such as the punch holding time *(T)*, the depth *(P)*, the thickness *(Ep)* and the material *(M)* sheet metal on the springback.

In the final analysis, we conclude that the holding time does not have a great influence on the springback whereas the material and the thickness of the sheet are the most dominant and overwhelming factors.

An empirical formulation of the springback in folding is proposed. Indeed, and through the response surfaces, the developed model is polynomial of second order. Altogether this empirical model is obtained after variation of the parameters of the process (*T*, *P*, *Ep* and *M*) at three different levels.

The difference between the values of springback predicted by this developed empirical model and those measured is small. The agreement between the two values measured and predicted by this model tells us that the developed model offers us a precise estimate of the springback.

Numerical modeling by simulation of the air V-bending procedure with the finite element calculation software (Abaqus), allowed us to determine the different bending parameters such as (bending angle during striking and withdrawal of the punch, radius of curvature) and thus predict the evolution of springback.

Meslameni and Ben Salem | J. Appl. Res. Ind. Eng. 8(3) (2021) 290-308

The simulation results thus developed are compared with those determined experimentally. The comparative study shows a good agreement between them, the differences between the different estimated and measured values are acceptable (around 1.07%).

References

[1] Gedekar, R. D., Kulkarni, S. R., & Kavad, M. B. (2008). Optimization of input process parameters affecting on springback effect in sheet metal 'V'bending process for CR2 grade steel sheet of IS 513-2008 material by using taguchi method. *International research journal of engineering and technology (IRJET)*, *5*(7), 381-386.

[2] Leu, D. K. (2019). Relationship between mechanical properties and geometric parameters to limitation condition of springback based on springback–radius concept in V-die bending process. *The international journal of advanced manufacturing technology*, *101*(1), 913-926. https://doi.org/10.1007/s00170-018-2970-1

[3] Wang, J., Verma, S., Alexander, R., & Gau, J. T. (2008). Springback control of sheet metal air bending process. *Journal of manufacturing processes*, *10*(1), 21-27. https://doi.org/10.1016/j.manpro.2007.09.001

[4] Bouhêlier, C. (1982). Sheet metal working, Heavy plate forming, Ed. *Techniques engineer*, B7 630. (**In French**). https://www.techniques-ingenieur.fr/base-documentaire/archives-th12/archives-travail-des-metaux-assemblage-tiabt/archive-1/formage-des-toles-fortes-b7630/

[5] Gandhi, A. H., & Raval, H. K. (2008). Analytical and empirical modeling of top roller position for three-roller cylindrical bending of plates and its experimental verification. *Journal of materials processing technology*, *197*(1-3), 268-278. https://doi.org/10.1016/j.jmatprotec.2007.06.033

[6] Trzepiecinski, T., & Lemu, H. G. (2017). Prediction of springback in V-die air bending process by using finite element method. *MATEC web of conferences* (Vol. 121, p. 03023). EDP Sciences. https://doi.org/10.1051/matecconf/201712103023

[7] Tao, J., Fu, Z., & Gao, H. (2019). Air bending of sheet metal based on the grey prediction model. *Journal of engineering science & technology review*, *12*(3), 123-129. DOI: 10.25103/jestr.123.17

[8] Aerens, R., Vorkov, V., & Duflou, J. R. (2019). Physics of large radius air bending. *Procedia manufacturing*, *29*, 161-168. https://doi.org/10.1016/j.promfg.2019.02.121

[9] Prastyo, Y., Adhi Yatma, W., & Hernadewita, H. (2018). Reduction bottle cost of Milkuat LAB 70 ml using optimal parameter setting with Taguchi method. *Journal of applied research on industrial engineering*, *5*(3), 223-238.DOI: 10.22105/JARIE.2018.138366.1041

[10] Khalili, S., & Mosadegh Khah, M. (2020). A new queuing-based mathematical model for hotel capacity planning: a genetic algorithm solution. *Journal of applied research on industrial engineering*, *7*(3), 203-220. DOI: 10.22105/JARIE.2020.244708.1187

[11] Onyekwere, O. S., Oladeinde, M. H., & Uyanga, K. A. (2020). Optimization of parameter settings to achieve improved tensile and impact strength of bamboo fibre composites. *Journal of applied research on industrial engineering*, *7*(4), 344-364. DOI: 10.22105/JARIE.2020.257974.1207

[12] Meslameni, W., & Kamoun, T. (2021). Detection of an imbalance fault by vibration monitoring: case of a screw compressor. *Journal of applied research on industrial engineering*, *8*(1), 27-39. DOI: 10.22105/JARIE.2021.269384.1243

[13] Satpute, S.A., & Chopade, R.P. (2018). Experimental study on spring back phenomenon in sheet metal V- die bending. *International research journal of engineering and technology*, *5*(6), 2323-2326.

[14] Özdemir, M. (2020). Optimization of spring back in air V bending processing using taguchi and RSM method. *Mechanics*, *26*(1), 73-81. https://doi.org/10.5755/j01.mech.26.1.22831

[15] Ben Ali, R.O.A., & Chatti, S. (2019). Modeling springback of thick sandwich panel using RSM, *The international journal of advanced manufacturing technology*, *103*, 3375–3387. https://doi.org/10.1007/s00170-019-03653-x

[16] Serban, F. M., Grozav, S., Ceclan, V., & Turcu, A. (2020). Artificial neural networks model for springback prediction in the bending operations. *Tehnički vjesnik*, *27*(3), 868-873. https://doi.org/10.17559/TV-20141209182117

[17] Guo, Z., & Tang, W. (2017). Bending angle prediction model based on BPNN-spline in air bending springback process. *Mathematical problems in engineering*, *2017*. https://doi.org/10.1155/2017/7834621

[18] Aerens, R., Vorkov, V., & Duflou, J. R. (2019). Springback prediction and elasticity modulus variation. *Procedia manufacturing*, *29*, 185-192. https://doi.org/10.1016/j.promfg.2019.02.125

[19] Wasif, M., Iqbal, S. A., Tufail, M., & Karim, H. (2020). Experimental analysis and prediction of springback in v-bending process of high-tensile strength steels. *Transactions of the Indian institute of metals*, *73*(2), 285-300. https://doi.org/10.1007/s12666-019-01843-5

[20] Karaağaç, İ. (2017). The evaluation of process parameters on springback in V-bending using the flexforming process. *Materials research*, *20*, 1291-1299. https://doi.org/10.1590/1980-5373-MR-2016-0799

[21] Vuong, G. H., & Nguyen, D. T. (2020). Studies on predicting spring-back and verifying the effects of temperature, sheet thickness and punch speed on forming force of v-bending for ss400 steel plate. In Parinov I., Chang SH., Long B. (Eds.), *Advanced materials* (pp. 97-108). Cham: Springer. https://doi.org/10.1007/978-3-030-45120-2_9

[22] Aerens, R., Vorkov, V., & Duflou, J. R. (2019). Springback prediction and elasticity modulus variation. *Procedia manufacturing*, *29*, 185-192. https://doi.org/10.1016/j.promfg.2019.02.125

[23] Miranda, S. S., Barbosa, M. R., Santos, A. D., Pacheco, J. B., & Amaral, R. L. (2018). Forming and springback prediction in press brake air bending combining finite element analysis and neural networks. *The journal of strain analysis for engineering design*, *53*(8), 584-601. https://doi.org/10.1177/0309324718798222