Optimization of Spring Back in Air V Bending Processing Using Taguchi and RSM Method

Mustafa ÖZDEMİR

Department of Machine and Metal Technology, Vocational School of Technical Sciences, Yozgat Bozok University, Yozgat, Turkey, E-mail: mustafa.ozdemir@bozok.edu.tr

1. Introduction

Sheet metal forming is of great importance in meeting the increasing needs of today's modern society. It can be seen in many applications in land, sea, air and space vehicles, various household goods and machines, industrial equipment, industrial structures as well as machine manu–facturing, defence industry, construction and energy sector, medical and in many other fields. Some of the most important factors in this type of common usage can be listed as their more rigid, cheap, easy machining, forming and joining properties compared to the other alternative materials.

Spring back in sheet metal products is of great importance in sheet metal production in order to solve geometric variables for the control of manufacturing processes and to obtain products having desired tolerances. This condition, which is called as spring back, is a problem which occurs after forming of sheet metal parts, is often an undesirable problem or a problem whose value should be considered if it is formed [1–4]. Estimation of the spring back values prevents the waste of time, workforce cost and the material loss used with trial and error method. Material savings, measurement accuracy at desired tolerance and quality and identical products can be obtained by determining or calculating the spring back angles. In this way, time and cost savings can be achieved by determining the ideal bending angle [5–7].

When some studies on sprinback in air *V*-bending technique are examined, Fei and Hodgson theoretically and experimentally investigated the effect of different thicknesses and geometric differences on spring back by using air *V*-bending technique in hot rolled TRIP steel [8]. Yilamu et al., investigated the spring back behaviour as a result of bending of stainless steel coated aluminium sheet in *V*-shaped air bending processes. Change of sheet thickness and bending angle before/after spring back was examined [9]. Fu and Mo used integrated neural network back propagation and genetic algorithm to develop the prediction model of spring back in the air bending process of high-strength sheet metal [10]. Vorkov et al., investigated the spring back behaviour of high strength steels experimentally with different parameters (different material, large radius punches, sheet thickness, die openings) using the air bending technique [11]. Vasudevan et al., investigated the spring back behaviours of electrogalvanised steel sheets in air bending operations. The effects of various parameters such as punch distance, punch speed, die opening, die radius, punch radius, orientation of the sheet and coating thickness on spring back behaviour were analysed [12]. Inamdar et al., examined the impact of various parameters on spring back for five sheet metals during air bending. The effective parameters related to spring back are identified as punch radius, die radius, die gap, sheet thickness, and angle of bend [13]. Garcia-Romeu et al., conducted trials in air bending of aluminium and stainless steel sheets to determine spring back values for different bend angles. Assessments were made concerning the effect of parameters on spring back [14]. In their study, Leu and Zhuang analysed how punch radius, sheet thickness, and material strength affected spring back in air *V* bending process. Theoretical examination was realised about impacts of the thickness ratio, normal anisotropy, and the strain-hardening exponent on the spring back angle in the *V* bending process for high-strength steel sheets [15]. Abdullah et al., used Taguchi method to examine optimisation in estimating the effect of various parameters on spring back of sheet metal in air *V* bending process. The experimental study was carried out on DP590 sheets having different thickness using various process parameters such as punch radius, die radius, die gap, and punch travel [16]. Ramadass et al., investigated spring back behaviour of Ti-Grade 2 sheets via finite element method and experimentation using the process parameters (punch radius, die opening, and sheet thickness). The simulation and experiments were carried out with Taguchi L_9 orthogonal array [17].

In the study, spring back behaviour was investigated by applying air V-bending process in DP600 sheet material. The effect of different thickness and punch tip radii on spring back values was investigated. In addition, experimental data were analysed with Response Surface Method (RSM) and Taguchi technic the experiment results. As a result of experimental study, the relationship between the parameters was examined and the most effective parameter was determined.

2. Spring back behaviour

Especially in sheet metal bending processes in sheet metal forming applications, it is necessary to take into account the amount of spring back in order to obtain products with desired angles and dimensions. In the sheet material forming process, spring back caused by the elastic return as a result of the lifting of the load from the material adversely affects the quality of the resultant products and may even cause serious geometric errors [18]. To minimise these errors, parameters such as material properties, material thickness, sheet anisotropy, bending angle, bending curve, bending force, punch tip radius etc. need to be known. When these parameters are controlled, products with appropriate angles and dimensions can be obtained.

As a result of the bending process, compressive stress in the internal deformation region and tensile stress in the external deformation region of the sheet material occur. When the load applied to the material was removed, the material bent due to the stresses in the internal and external parts slightly stretch back (Fig. 1). Spring back angle SB is equal to the difference between the bending angle $θ'$ obtained after removing the punch and the starting bending angle $θ$ ($SB = θ' - θ$).
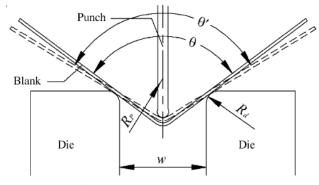

Fig. 1 Air *V* bending process [8]

3. Material and method

In the experimental study, DP600 (Dual Phase steel) sheet materials with the thicknesses of 2, 3, 4 and 5 mm were used. The samples were prepared by cutting with a hydraulic shear at 30x80 mm dimensions and in 0° rolling direction. Burrs forming on the side surfaces due to the cutting process were cleaned using an abrasive disk. Table 1 shows the chemical composition and mechanical properties of the sheet materials used in the experimental study.

Table 1

Properties of materials used in the experimental study

C	Mn	P	S	Si	Al	Cu
0.089	1.63	0.046	0.007	0.34	0.025	0.018
Mechanical properties						
Tensile strength, MPa	620	Yield strength, MPa				400
Ultimate strength, MPa	680	Young's Modulus, GPa				210

In the air V-bending technique, the effect of sheet material thickness and punch tip radius on spring back *SB* was investigated. Therefore; forming processes of DP600 sheet materials with the thicknesses of 2, 3, 4 and 5 mm were

performed using dies having punch tip radii of *R*2, *R*4, *R*6, and *R*8 mm. Table 2 shows the process parameters used in the study.

Table 2

Tool and process parameters

Parameter	Dimension
Work blank, *L*×*W*×*T*, mm	80x30x(2, 3, 4, 5)
Punch radius, *Rp*, mm	2, 4, 6, 8
Die radius, *Rd*, mm	5
Die opening, *Wd*, mm	27, 29, 31, 33
Punch velocity, *V*, m/dak	50

In order to conduct the experimental study, the air V-bending die was designed and manufactured. The male puncher and female die of the bending die used in the experimental study were manufactured sensitively from C1390 shear steel in the wire erosion workbench. In the bending die material, abrasion may occur due to friction.

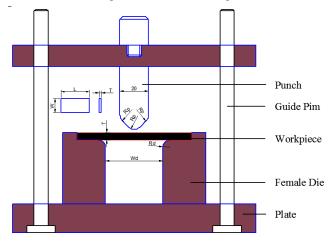Therefore, stress relief annealing was applied on the die material. Fig. 2 shows the bending die.

Fig. 2 Air *V* bending die used in the experimental study

The tests were carried by leaving a gap as thick as a sheet between the punch and die at the air bending force and punch stroke rate *V* of 50 m/min. As shown in experimental parameters in Table 3; 16 parameters were used in the tests where 4 different thicknesses and 4 different punch tip radii were used. Each test was repeated 10 times and a total of 160 tests were performed. While the test results were evaluated, the spring back graphs were drawn by taking the arithmetic means of the repeated values.

Table 3

Bending parameters used in the experimental study

Material	Sheet thickness, mm	Punch radius *Rp*, mm	Yield strength, MPa	Die opening *Wd*, mm	Number of tests
DP600	2	2	400	27	40
	3	4		29	40
	4	6		31	40
	5	8		33	40
Number of total experiments					160

After the tests, the test samples were measured separately. Measurements were first made using a protractor. After the pre-measurement process, each sample was subjected to a second precise measurement process by using DEA 081206 pioneer brand a coordinate measuring machine CMM. The test specimen was placed parallel to the

ground 90°. 8 points were determined on inner surfaces of the sample in the measurement processes and the angle values between these points were measured precisely (Fig. 3). By this means, possible errors in the measurement were minimised and the reliability of the results was ensured.
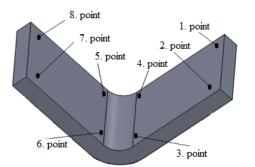
Fig. 3 Points taken in *CMM* device

4. Taguchi and RSM method

The Taguchi method was developed to improve the implementation of total quality control. The Taguchi method is an effective analysis method used to optimize the bending parameters affecting the production process. The experimental design performed by using this method leads to a significant decrease in number of experiments as well as minimization in time loss.

The response surface methodology RSM is an effective analysis method used to optimize the bending parameters that affect the production process. In the experiments carried out using this test design method, material and time losses are minimized by decreasing the number of experiments significantly.

The RSM is beneficial to solve the problems in which various variables directly have a direct impact on response of the problem. It is possible to examine the effect of several factors on quality criteria and achieve optimum values via RSM. RSM design ought to have minimum three levels for each factor (Table 4). Input variable, output variable and error are the important terms concerning RSM which exactly identifies its purpose in the problems for DOE. Normally first-order response model factorial design matrix is not used because of the lack of fit [19, 20]. The tests are realised with CCD matrix developing a second order response model. Central composite rotatable design (CCRD) containing the alpha value of 1.41421 and 13 non-centred points and 5 centred points was utilised in this study. Table 5 shows the test having 16 repetitions and the related response variables.

Table 4

A two factor and four level design for experimentation

Process parameters	Level 1	Level 2	Level 3	Level 4
Sheet thickness (mm)	2	3	4	5
Punch radius (mm)	2	4	6	8

Table 5

Design of experiments

Experimental No.	Sheet thickness T, mm	Punch radius R, mm
1	2	2
2	2	4
3	2	6
4	2	8
5	3	2
6	3	4
7	3	6
8	3	8
9	4	2
10	4	4
11	4	6
12	4	8
13	5	2
14	5	4
15	5	6
16	5	8

study, the formula given in Eq. (1) referring to the principle of "the smallest is the best" was used [20, 21].

$$S/N = -10log\left(\frac{1}{n}\sum_{i=1}^{n}Y_i^2\right). \qquad (1)$$

The relationship between the parameters was investigated by using RSM and Taguchi method. Table 4 shows two factors and four levels used in experimental design. Table 5 shows the experimental set prepared with Taguchi technique of the parameters used in the experimental study.

5. Results and discussions

The effect of sheet material thickness and punch tip radius on amount of spring back in Air *V*-bending technique was investigated. The results obtained after bending processes were analysed using the Responsible Surface Method (RSM) and Taguchi technique of the MINITAB 16 program. Simulation spring back values and the relationship between them were investigated by analysing the experimental results in RSM. In the Taguchi method, the optimum bending parameters required for the lowest spring back value were determined by selecting the smallest *S/N* ratio. In the MINITAB 16 program, *S/N* and level values were calculated by selecting the equation of "the smallest is the best". Table 6 shows the experimental results, simulation results obtained with RSM and Taguchi technique, and *S/N* ratios. Table 7 shows the results of *S/N* ratios obtained based on sheet material thickness and punch tip radii. When the simulation and experimental results were compared with each other, Fig. 4 shows that they were

In the study, Taguchi method was used as experimental design and analysis method. A statistical performance measure known as the *S/N* ratio is used to analyse the test results. The evaluation was made by converting the results obtained from the tests into signal-to-noise ratio *S/N*. In *S/N* ratio, *S* and *N* refer to signal and noise factors, respectively. While the signal factor refers to the actual value taken from the system, the noise factor refers to the factors that affect the test result but could not be included in the experimental design. In the calculation of *S/N* ratios, the methods of "nominal is best", "the smallest is the largest" and "the smallest is the best" depending on the characteristic type are used. Since the spring back value was requested to be minimum to determine *S/N* values in this

similar with each other. Fig. 4 shows the polynomial curve equations of the test results obtained in the bending process conducted with different punch tip radii. It was determined that the spring back value increased as the punch tip radius increased. In Taguchi method, the most basic criteria for the analysis of experimental data is the signal/noise *S/N* ratio. In this study, the *S/N* ratio should have the maximum value in order to obtain the optimum parameter according to the Taguchi method. Accordingly, the most optimum bending parameter in Table 6 was found to be -14.93 *S/N* ratio for spring back. Optimum bending conditions were obtained for the lowest spring back value in 5 mm sheet material thickness and *R*2 mm punch tip radius.

Table 6

Design of experiments and measured responses

Experimental No.	Sheet thickness *T*, mm	Punch radius *R*, mm	Experimental spring back, °	Simulation spring back, °	*S/N* ratio
1	2	2	10,42	10,40	-20,36
2	2	4	10,66	11,17	-20,56
3	2	6	11,98	11,69	-21,57
4	2	8	12,20	11,96	-21,73
5	3	2	9,70	9,56	-19,74
6	3	4	10,64	10,41	-20,54
7	3	6	10,80	11,01	-20,67
8	3	8	11,05	11,36	-20,87
9	4	2	8,12	8,01	-18,19
10	4	4	9,10	8,94	-19,18
11	4	6	9,58	9,62	-19,63
12	4	8	9,96	10,06	-19,97
13	5	2	5,58	5,74	-14,93
14	5	4	6,54	6,76	-16,31
15	5	6	7,80	7,52	-17,84
16	5	8	8,10	8,04	-18,17

a

$$y = -0.005x^2 + 0.691x + 9.625$$
$$R^2 = 0.9032$$

t=2 mm

b

$$y = -0.1725x^2 + 1.2835x + 8.6325$$
$$R^2 = 0.9637$$

t=3 mm

c

$$y = -0.15x^2 + 1.35x + 6.94$$
$$R^2 = 0.9958$$

t=4 mm

d

$$y = -0.165x^2 + 1.707x + 3.975$$
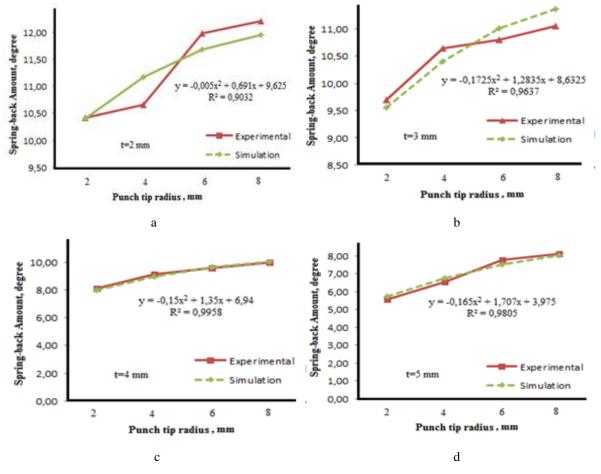$$R^2 = 0.9805$$

t=5 mm

Fig. 4 Effect to spring back amount of different punch tip radius

The fact that *R*2 values of the test results, obtained as a result of the bending processes, for polynomial curve equation are close to 1 shows the sensitivity of the experimental results. After spring back, the radius of bending zone increased. The effect of the Bending radius *R* on spring back is related to the *R/T* ratio. As the *R/T* ratio increases, the spring back value on the sheet material also increases [3]. As the bending radius value increases, forces

coming to the die decrease. Therefore, in parallel to the literature, as the punch type radius value increased, spring back values also increased.

Table 7

Response table for signal to noise ratios

Level	T	R
1	-21,05	-18,30
2	-20,45	-19,15
3	-19,24	-19,93
4	-16,81	-20,18
Delta δ	4,24	1,88
Rank	1	2

Fig. 5 shows the graph of the level values given in Table 6. In order to determine the optimum bending conditions of the experiments to be performed under the same conditions, interpretation can be made based on the level values of the sheet thickness and punch tip radius factors stated in Fig. 5 and in Table 6. In this case, the fourth level of the sheet thickness factor $A4$, first level of the punch tip radius $B1$ are seen to be high in Fig. 6.

Therefore, the optimum bending parameters determined under the same conditions for the future tests would be 5 mm for sheet thickness and 2 mm for thepunch radius. When the effect of bending parameters on spring back was also examined in Table 7, the maximum δ value referred to the most effective parameter. Therefore, sheet material thickness T was determined to be more effective factor than punch tip radius R.

Concerning the interaction of each factor, Fig. 7 shows a significant interaction between all parameters at different levels. However, the effect of these parameters becomes marginal at higher Reynolds number given that the Reynolds number has the highest impact on the spring back.
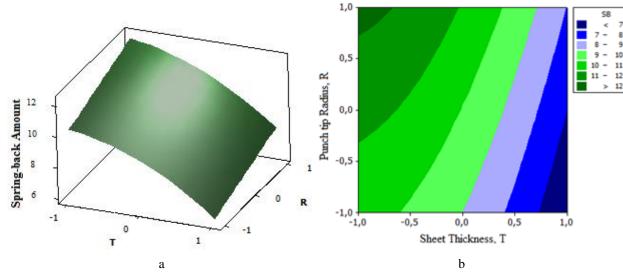

Fig. 5 The effect to spring back of sheet thickness and punch tip radius: a - 3D surface, b - contour plot
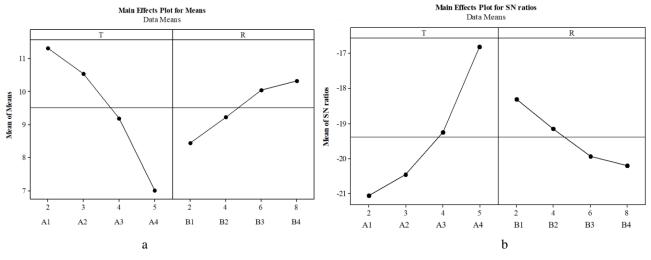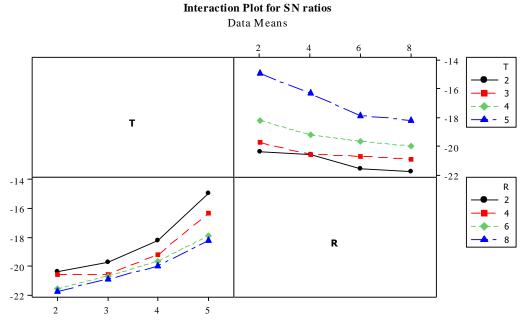

Fig. 6 Response of (a) mean (b) *S/N* ratio of different parameters

Fig. 8 shows the residual graphs of the model developed for spring back in the bending process to check the adequacy. When the distributions were normal, the normal residue graph yielded residual values compared to the expected values. The normal graph of the remaining residues showed that the data complied with the sample size rules and confidence intervals on the straight line, and that the p values were correct. Ideally for the remaining and installed plots, all points should fall randomly on both sides of the zero as in the recognizable pattern. Fig. 8 clearly shows that all points fit on both sides of zero and no unstable variance or contradiction is observed. He confirmed that the residues were randomly distributed with constant variances. The order versus residue graph showed the order in which

Interaction Plot for SN ratios
Data Means

Signal-to-noise: Smaller is better

Fig. 7 The interactions of bending parameters with respect to spring back

the data was collected and the patterns during the observation and at the points. Ideally, the residue remaining on the plot should fall randomly around the center line.

Fig. 8 clearly shows that the residues close to each other are correlated and therefore not independent [22-24].
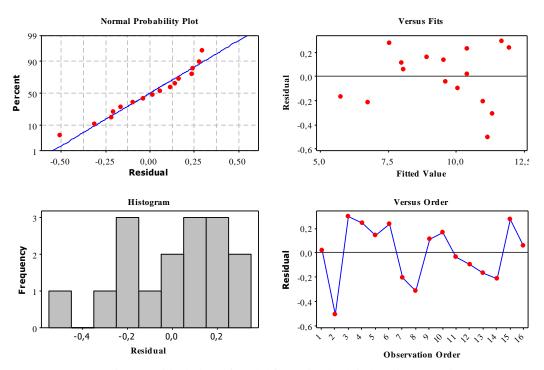

Fig. 8 Residual plots of model for spring back in bending operation

While determining the optimum bending parameters from the *S/N* ratio obtained with Taguchi method, the relationship between the bending parameters was determined using the analysis of variance. The relationships between the sheet thickness and punch radius of *S/N* were evaluated. Table 8 shows the full quadratic analysis results of RSM. According to RSM results, the significance level should be $p<0.05$.

According to these results, the most significant value was sheet thickness and punch tip radius, respectively. Sheet thickness and punch radius showed the activity at the confidence level of 95%. These results also confirmed the order of importance in Table 8. Eq. (2) and Table 8 show the spring back (*SB*) regression equation and equation coefficients, respectively.

$$SB = 10,1113 - 2,1431 xT + 0,9634 xR - 0,7973 xT^2 - 0,2770 xR^2 + 0,1861 xTxR.. \qquad (2)$$

Estimated regression coefficients for SB

	Coef	*SE* Coef	*T*	*P*
Constant	10,1113	0,14562	69,435	0,000
T	-2.1431	0,09619	-22,279	0,000
R	0.9634	0,09619	10,015	0,000
T^2	-0.7973	0,16132	-4,943	0,001
R^2	-0.2770	0,16132	-1,717	0,117
TxR	0,1861	0,12906	1,442	0,180
Model Summary S=0,286795 R^2 =98,43% R^2 (*adj*)=97,64%				

In the second-degree regression equation, the determination coefficient R^2 (*adj*) was 97.64%. Obtaining the determination coefficient which is close to one indicates the strength of the interaction between the variables. 97.64% of the change in the *SB* value was explained by independent variables. It was determined in second-degree regression equation to *SB* dependent variable that in Table 8, *T* and *R* factors and T^2 interaction was significant ($p<0.05$) at significance level of 5% but R^2 and *TxR* interaction were not significant since they were greater than $p<0.05$ value.

Table 9 shows the results of the analysis of variance carried out to determine the effect level of the bending factors on spring back. Here, *F* values and percent effect rates showing the significance level of each variable are seen. This analysis was performed at confidence level of 95% and significance level of 5%.

The effect of control factors is determined by the comparison of *F* values. The factor with the greatest *F* value is considered as the most effective factor on the result. When the results of the analysis of variance in Table 9 were examined, it was observed that *T* had the greatest effect in terms of the *F* value, followed by *R*. The contributions of *T* and *R* to the test results were found to be 78.02% and 15.77%, respectively. Table 10 shows the regression coefficients obtained when the model was reconstructed by removing the ineffective parameters from the variance analysis and Table 11 shows the reconstructed analysis of variance. Eq. (3) shows the reconstructed spring back model.

$$SB = 9.9573 - 2,1431xT + 0,9634xR - 0,7973xT^2. \quad (3)$$

Table 12 shows spring back values α_1, simulation results α_2 obtained as a result of the bending processes and the estimated spring back values α_3 obtained after the reconstruction of the model by removing the non-effective elements. In addition, errors between α_1-α_2, α_1-α_3 and α_1-α_3 values and total error values are also given.

When the spring back values in Fig. 9 were compared, it was observed that high convergence values of 97.21% were obtained for *SB*. In this context, it was remarkable that the difference between the results of the verification test and the results obtained from the Taguchi approach was negligible. Based on these results, it is possible to say that Taguchi optimization was successfully applied at significance level of 0.05.
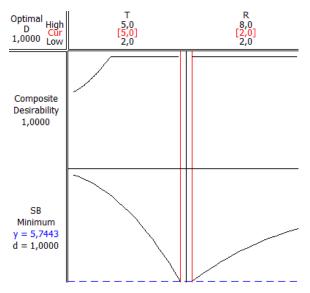

Fig. 9 Comparison of the prediction model and experimental results

Analysis of variance for *SB*

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	p	Contribution, %
T	1	40,8265	40,8265	40,8265	496,36	0,000	78,03
R	1	8,2497	8,2497	8,2497	100,30	0,000	15,77
T^2	1	2,0093	2,0093	2,0093	24,43	0,001	3,84
R^2	1	0,2426	0,2426	0,2426	2,95	0,117	0,46
TxR	1	0,1710	0,1710	0,1710	2,08	0,180	0,33
Residual Error	10	0,8225	0,8225	0,823			1,57
Total	15	52,3216					100

Coefficients obtained in the reconstructed regression equation

	Coef	*SE* Coef	*T*	*P*
Constant	9,9573	0,1284	77,525	0,000
T	-2.1431	0,1076	-19,909	0,000
R	0.9634	0,1076	8,949	0,000
T^2	-0.7973	0,1805	-4,417	0,001
Model Summary S=0,320943 R^2=97,64% R^2 (adj)=97,05%				

Table 11

Newly generated variance analysis

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	p	Contribution, %
T	1	40,8265	40,8265	40,8265	396,36	0,000	78,03
R	1	8,2497	8,2497	8,2497	80,09	0,000	15,77
T^2	1	2,0093	2,0093	2,0093	19,51	0,001	3,84
Residual Error	12	1,2361	1,2361	0,1030			2,36
Total	15	52,3216					100

Table 12

Predicted response for new design points using model for SB

Experiment spring back α_1	Simulated spring back α_2	New design α_3	Error $\alpha_1 - \alpha_2$	Error $\alpha_1 - \alpha_3$	Error $\alpha_2 - \alpha_3$
10,42	10,40	10,3397	-0,02	0,0803	0,0603
10,66	11,17	10,9820	0,51	-0,322	0,188
11,98	11,69	11,6242	-0,29	0,3558	0,0658
12,20	11,96	12,2665	-0,24	-0,0665	-0,3065
9,70	9,56	9,6197	-0,14	0,0803	-0,0597
10,64	10,41	10,2620	-0,23	0,378	0,148
10,80	11,01	10,9043	0,21	-0,1043	0,1057
11,05	11,36	11,5465	0,31	-0,4965	-0,1865
8,12	8,01	8,1910	-0,11	-0,071	-0,181
9,10	8,94	8,8332	-0,16	0,2668	0,1068
9,58	9,62	9,4755	0,04	0,1045	0,1445
9,96	10,06	10,1178	0,10	-0,1578	-0,0578
5,58	5,74	6,0535	0,16	-0,4735	-0,3135
6,54	6,76	6,6957	0,22	-0,1557	0,0643
7,80	7,52	7,3380	-0,28	0,462	0,182
8,10	8,04	7,9803	-0,06	0,1197	0,0597
Total Eror ∑=			0,02	0,0001	0,0201

6. Conclusions

The experimental results obtained as a result of air *V*-bending process by using different thicknesses and punch radii for Dp600 sheet material are given below.

✓ Experimental and simulation results were observed to be in compliance with each other.

✓ It was determined that as the punch tip radius increased, the spring back value increased; on the other hand, as the sheet thickness increased, the spring back value decreased.

✓ The contributions of the process variables were examined in the air *V* bending process for minimizing spring back. The sheet thickness had the maximum contribution (78.02%), the contribution of punch radius was ranked as the second with the rate of 15.77%. As a result of the regression models and Taguchi analysis conducted in the determination of effective parameters, the most effective parameter on *SB* was found to be sheet thickness.

✓ As a result of the experiments conducted according to Taguchi technic, *S/N* ratios of spring back were found. By using "the smallest is the best" *S/N* ratio equation, the maximum value was sought in *S/N* ratio. The maximum *S/N* ratio gave the optimum bending parameters. In bending operations, optimum bending conditions corresponding to the maximum of -14.93 *S/N* for the lowest spring back were obtained as punch type radius of 2 mm and sheet thickness of 5 mm.

✓ The confirmation tests were carried out for verification of optimal bending parameters. The spring back values reduced from the baseline bending parameters to optimal bending parameters with the rate of approximately 97.12%.

References

1. **Thipprakmas, S.; Phanitwong W.** 2011. Process parameter design of springback and spring-go in V-bending process using Taguchi technique, Materials and Design 32: 4430-4436.
https://doi.org/10.1016/j.matdes.2011.03.069.
2. **Özdemir, M.; Gökmeşe, H.** 2018. Microstructural characterization and deformation of X10CrAlSi24 sheet material applied V-bending process, Tehnički vjesnik 25(3): 846-854.
https://doi.org/10.17559/TV-20170425022545.
3. **Özdemir, M.** 2017. Mathematical modeling of the effect of different parameters on spring back in sheet metal formability process, American Journal of Engineering Research (AJER) 6(10): 198-205.
4. **Liu, X.; Zhao, S.; Qin, Y.; Zhao, J.; Wan-Nawang, W. A.** 2016. A parametric study on the bending accuracy in micro W-bending using Taguchi method, Measurement 100: 233-242.
https://doi.org/10.1016/j.measurement.2016.12.007.
5. **Ankenas, R.; Barauskas, R.** 2006. Finite element investigation on parameters influencing the spring back during sheet metal forming, Mechanika 5(61): 57-61.
6. **Shukla, R.; Gautam, V.** 2014. Experimental and numerical analysis of negative spring back in interstitial free (IF) steel, International Journal of Advance Research and Innovation 2: 232-236.

7. **Wang, J.; Verma, S.; Alexander, R.; Gau, J. T.** 2008. Spring back 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.

8. **Fei, D.; Hodgson, P.** 2006. Experimental and numerical studies of spring back in air V-bending process for cold rolled TRIP steels, Nuclear Engineering and Design 236(18): 1847-1851. https://doi.org/10.1016/j.nucengdes.2006.01.016.

9. **Yilamu, K.; Hino, R.; Hamasaki, H.; Yoshida, F.** 2010. Air bending and spring back of stainless steel clad aluminum sheet, Journal of Materials Processing Technology 210(2): 272-278. https://doi.org/10.1016/j.jmatprotec.2009.09.010.

10. **Fu, Z.; Mo, J.** 2011. Spring back prediction of high-strength sheet metal under air bending forming and tool design based on GA–BPNN, The International Journal of Advanced Manufacturing Technology 53(5-8): 473-483. https://doi.org/10.1007/s00170-010-2846-5.

11. **Vorkov, V.; Aerens, R.; Vandepitte, D.; Duflou, J. R.** 2017. Experimental investigation of large radius air bending, The International Journal of Advanced Manufacturing Technology 92(9-12): 3553-3569. https://doi.org/10.1007/s00170-017-0346-6.

12. **Vasudevan, D.; Srinivasan, R.; Padmanabhan, P.** 2011. Effect of process parameters on springb ack behaviour during air bending of electro galvanised steel sheet, Zhejiang Univ-Sci A (Appl Phys & Eng) 12(3):183-189. https://doi.org/10.1631/jzus.A1000055.

13. **Inamdar, M. V.; Date, P. P.; Sabnis, S. V.** 2002. On the effects of geometric parameters on spring back in sheets of five materials subjected to air vee bending, Journal of Materials Processing Technology 123(3):459-463. https://doi.org/10.1016/S0924-0136(02)00136-X.

14. **Garcia Romeu, M. L; Ciurana, J.; Ferrer, I.** 2007. Spring back determination of sheet metals in an air bending process based on an experimental work, Journal of Materials Processing Technology 191(1-3):174-177. https://doi.org/10.1016/j.jmatprotec.2007.03.019.

15. **Leu, D. K.; Zhuang, Z. W.** 2016. Spring back prediction of the vee bending process for high-strength steel sheets, Journal of Mechanical Science and Technology 30(3): 1077-1084. https://doi.org/10.1007/s12206-016-0212-8.

16. **Abdullah, S. A.; Buang, M. S.; Saedon, J.; Abdullah, H.** 2015. Desıgn parameters selectıon of sprıng back effect in aır-V bending usıng Taguchı approach on advance hıgh strength steel-Dp590, Journal Teknologi (Sciences & Engineering) 76: 69-73. https://doi.org/10.11113/jt.v76.5514.

17. **Ramadass, R.; Sambasivam, S.; Thangavelu, K.** 2019. Selection of optimal parameters in V-bending of Ti-Grade 2 sheet to minimize spring back, Journal of the Brazilian Society of Mechanical Sciences and Engineering 41(1): 21. https://doi.org/10.1007/s40430-018-1521-x.

18. **Tekaslan, Ö.; Gerger, N.; Şeker, U.** 2008. Determination of spring-back of stainless steel sheet metal in "V" bending dies, Materials and Design 29(5): 1043-1050.

https://doi.org/10.1016/j.matdes.2007.04.004.

19. **Taguchi, G.; Chowdhury, S.; Wu, Y.** 2005. Taguchi's Quality Engineering Handbook, John Wiley & Sons, Inc., New Jersey, USA.

20. **Wei, L.; Yuying, Y.; Zhongwen, X.; Lihong, Z.** 2009. Spring back control of sheet metal forming based on the response-surface method and multi-objective genetic algorithm, Materials Science and Engineering: A 499(1-2): 325-328. https://doi.org/10.1016/j.msea.2007.11.121.

21. **Günay, M.; Yücel, E.** 2013. Application of Taguchi method for determining optimum surface roughness in turning of high-alloy white cast iron, Measurement 46: 913-919.

22. **Yoon, H. S.; Wu, R.; Lee, T. M.; Ahn, S. H.** 2011. Geometric optimization of micro drills using Taguchi methods and response surface methodology, Int. J. Precis. Eng. Manuf. 12: 871–875. https://doi.org/10.1007/s12541-011-0116-6.

23. **Sahu, N. K.; Andhare, A. B.** 2017. Modelling and multi objective optimization for productivity improvement in high speed milling of Ti–6Al–4V using RSM and GA, J Braz. Soc. Mech. Sci. Eng. 39: 5069–5085. https://doi.org/10.1007/s40430-017-0804-y.

24. **Hosseini, A.; Farhangdoost, K.; Manoochehri, M.** 2012. Modelling of extrusion process and application of Taguchi method and ANOVA analysis for optimization the parameters, Mechanika 18(3): 301-305. http://dx.doi.org/10.5755/j01.mech.18.3.1881.

M. Özdemir

OPTIMIZATION OF SPRING BACK IN AIR V BENDING PROCESSING USING TAGUCHI AND RSM METHOD

S u m m a r y

In this study, spring back behaviour of Dp600 (Dual Phase Steel) sheet material was investigated using air *V* bending technique. As bending parameters, four different punch tip radii and four different sheet thicknesses were used. The spring back values obtained from the experiments were compared with each other. At the same time, the experimental data were analysed with Response Surface Method (RSM) and Taguchi technic. The experimental data and the simulation results were found to be consistent. The signal-to-noise *S/N* ratio is used to determine the most appropriate parameter of minimum spring back behaviour. Additionally, it is possible to estimate the optimal combination of the bending parameters. The signal-to-noise *S/N* ratio and the design of experiment (DOE) were utilised for the analysis of the experimental results. It was determined that the effect of these parameters on the air V bending process was based on spring back behaviours.