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INVESTIGATION ON SPRING-BACK EFFECT OF GALVANIZED IRON SHEET

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Abstract: Sheet metal bending is a useful process utilized in varying applications. Investigations in sheet bending find its importance as it is subjected to spring-back upon withdrawal of load and it differs based on material property and its size, etc. Therefore, maintaining specification of a bent object requires appropriate strategy to adopt. In this work, influence of thickness of galvanised iron sheet metal, punch radius and die corner radius on spring-back is considered. Three different values are taken for punch radius, die corner radius and thickness. Experiments are designed according to response surface methodology (RSM) and analysed by ANOVA technique. From various contour plots and surface plots, it is observed that sheet thickness has significant effect on spring-back. Influence of other two parameters is comparatively less if considered individually, but the combined effect is quite significant.

Keywords: Modeling, Spring-back, Finite Element Method, FEM, Experimental validation, Suppressing spring-back.

1. INTRODUCTION

Sheet metal bending process is employed to manufacture sheet metal products, used commonly in aerospace, defence and automobile industry. Flat sheet metal is held firmly between die and blank holder in this process. The sheet gets plastically deformed when the punch moves downward and goes into die cavity and the corresponding shape of punch and die set is formed. Spring-back happens after the punch is removed as shown in Fig.1. This phenomenon results in the deviation from the design specification of the obtained product shape and may be the main cause of assembly difficulties.

Using sheet metal bending, a metallic sheet can be plastically deformed to a desired shape. Stress induced within the sheet metal is beyond yield strength, but below ultimate tensile strength. The volumetric change is nearly insignificant for this process. The influencing factors in the mechanics of sheet metal bending are radius of bend, width over which bending is done, material, sheet thickness, bend angle, tooling, bending process used, etc. [1].

Bending processes can be divided into two broad classifications depending on their

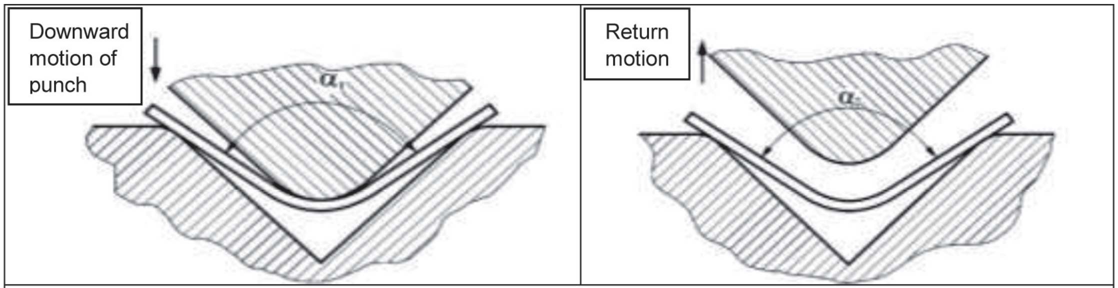


Fig. 1. Spring-back phenomenon during bending of a sheet metal in a V shaped die (α_1 is bend angle at the end of punch downward movement, and α_2 is angle after spring-back, $\alpha_1<\alpha_2$)

usage in industry, one is V-bending and another one is air bending. Air bending is employed in large scale production where accuracy is not desired so much but in V-bending process, the bend products take shape similar to the shape of a die profile without considering spring-back [2].

While using finite element analysis to estimate spring-back in sheet metal, usually some discrepancy is observed between the magnitude of it obtained in simulation and that experienced in reality and it is always difficult to determine the reason, particularly when the geometry of the product is intricate [3]. Spring-back phenomenon in metals depends on different parameters such as variation of elastic properties of a material, elastic-plastic anisotropy and material hardening. Important of these are the method of unloading, the scheme of time integration, the choice of element, the discretization of blank and tool and the algorithm of contact used.

Simple analytical solutions for spring back angle calculation in plane-strain pure bending was derived several decades ago. In sheet metal forming, analytical solutions for spring-back were calculated for edge bending [4, 5]. For analytical modeling of spring-back, variation in elastic property, anisotropy of sheet material, description of material yielding, hardening effect were considered in some works [6-13]. Many other investigations were carried out [14-35] on modelling of spring-back effect and on experimental investigation on it.

Gomes et al. noticed [11] the spring-back in high strength steel numerically and experimentally due to material ansitropy. Three yield criteria were considered during numerical simulation, such as von Misses yield criteria, Barlat ansitopic yield criteria and Hill's yield criteia. The spring-back phenomenon is sensitve to various process and geometrical parameters such as punch velocity, temperature, punch force, blank holding force, die corner radius, punch tip radius, bend angle, thickness, etc. Many research works were carried out to investigate the effects of these parameters on spring-back reduction. Panthi et al. investigated [12] on spring-back based on large elastic deformation algorithm by employing a software, RRL-FEM capable of handling large deformation and material rotation. With the increase in radius of die, force requirement per unit length was reported to have decreased. A rate independent anisotropic plasticity model considering Bauschinger effect was proposed [13] by Firat et al. and then, the model was implemented in FEM software utilizing Hill's quadratic yield function as the yield criteia.

Spring-back can be reduced by employing suitable process and geometrical parameters. Besides these methods, there are certain compensatation technique available to effectively eliminate the adverse effect of spring-back. A novel technology was proposed [15] to effectively control the spring-back during air bending process by employing a pre-determined final punch position, while effects of important parameters, such as thickness, ansitropy and punch radius, on spring-back in U-die and V-die bending of an anisotropic steel were explored [16] in another work. It was observed that increasing the sheet thickness resulted in a decrease in spring-back, and spring-go which is just opposite phenomenon of spring-back. Eggertsen et al. observed [17] the spring-back deformation on different types of steels experimentally and also employing LS-DYNA using five hardening models, namely isotrpic hardening model, mixed kinematic-isotropic hardening model, Armstrong-Frederick hardening model, Geng-Wagoner hardening model and Yoshida-Uemori hardening model. Yoshida-Uemori model and Geng-Wagoner model yielded the best fit with less than 2% deviation from the experimental values.

Yu worked on [18] the change in elastic modulus during U channel bending type plastic deformation in a steel, Yilamu et al. [19] found the spring-back phenomenon in a stainless steel clad aluminium sheet in V-die air bending, whereas Chongthairungruang et al. investigated [23] on spring-back phenomenon of steels by U-die bending numerically using LS-DYNA with the use of planar anisotropic models according to Hill's 1948, Barlat's yield 2000 and Yoshida-Uemori model, and also through experiments. Sumikawa et al. proposed [31] a material model for high strength steel sheets to predict spring-back accurately. They recommended that elastic as well as plastic anisotropy should not be ignored for anisotropic material for better spring-back prediction. A new analytical hardening model named anisotropic nonlinear kinematic hardening model was employed [32] based on Hill's 1948 yield criteria to accurate prediction of spring-back in U-die bending of normal and pre-strained DP780 dual phase steels.

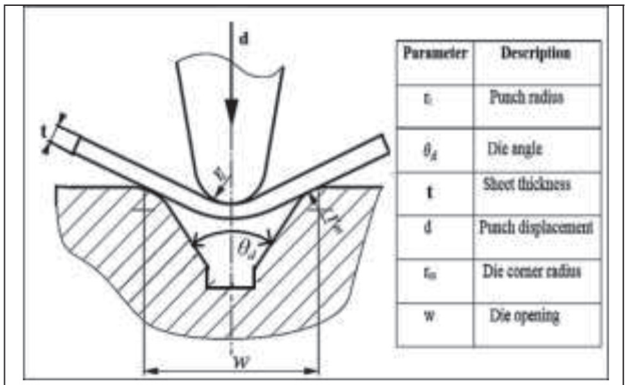
Spring-go or spring-back phenomena were investigated on different materials by Thipprakmas et al. [14], Ouakdi et al. [22], Hakan et al. [24], Syeed et al. [27], Krinninger et al. [29], Slota et al. [34] using finite element method and/or through experimets. Lawanwomg et al. tried [26] to eliminate spring-back by employing a novel technology in HSS sheet U-die bending where the bottom plate was additionaly bent with a counterpunch at the final stage of U-bending. An experimental and numerical investigation [28] was carried out by Choi and Huh to study the effect of punch velocity on the amount of spring-back of auto-body steel sheet in U-die bending. An investigation was carried out [34] to study the effects of channel width in U-die bending process on spring-back characteristics of aluminium sheet. Young et al. proposed [25] a spring-back compensation technique based on modified displacement adjustment algorithm to adjust the height of punch. Balon et al. introduced [30] a new technology to compensate the effects of spring-back by correcting the dimension of the forming and trimming die.

In this work, it is tried to find out the contribution of sheet thickness, punch radius and die corner radius on spring-back through simulation and its experimental validation. Different die and punch sets have been made and sheets of galvanised iron have been chosen. Therefore, the aim is to investigate the effect of geometrical parameters on spring-back towards its minimization.

2. EXPERIMENTAL DETAILS

In this investigation, galvanised iron sheets are bent in V-die which is clamped in universal testing machine (UTM) (make: Lab Equipments & Chemicals, Kolkata, capacity: 200 kN, resolution: 0.4 kN). For various combinations of geometrical parameters designed as per Response Surface methodology, spring-back is measured. Digital vernier height gauge (make: Mitutoyo, Japan, range: 0-300 mm, resolution: 0.01 mm) is used for the measurement.

Three values of punch radius ri taken (Fig. 2) are 4 mm, 8 mm and 12 mm for a constant die valley angle of 60 degree. Die corner radius rm chosen is of 10 mm, 15 mm and 20 mm. Width of die as well as punch is taken as 85 mm, and material selected for die and punch is high carbon high chromium steel. Die opening, W in this case is taken as 70 mm and theoretical die depth should be 60.5 mm but due to different values of punch radius, value of die depth is chosen by trial and error method considering all the constraints.



Parameter	Description
r_i	Punch radius
θ_d	Die angle
t	Sheet thickness
d	Punch displacement
r_m	Die corner radius
w	Die opening

Fig. 2. Geometrical parameters affecting spring-back

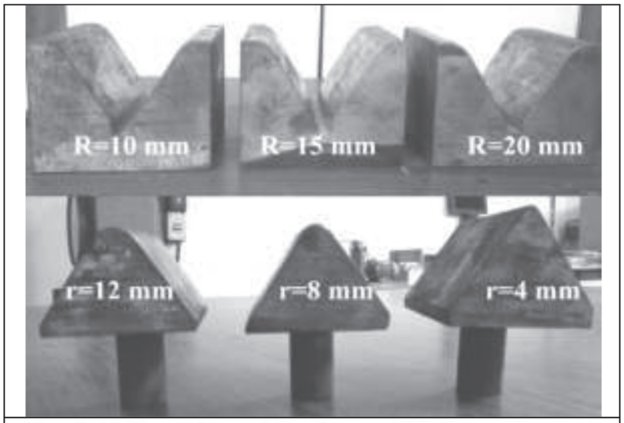


Fig. 3. Different combinations of V-die and punch

Length of sheet (L) is taken as 150 mm, width (W) 50 mm and three different values for thickness (t) is 0.5 mm, 1 mm and 1.5 mm. The large piece of galvanised iron sheet is cut in a sheet cutting press according to dimension needed for experiments. Each sheet is marked according to serial number of experiments conducted. Chemical composition for the galvanised iron sheet material used is given in Table 1. Important mechanical properties of this material are presented in Table 2.

Table 1: Chemical composition of galvanised iron sheet

C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Ni (%)	Mo (%)
0.036	0.019	0.222	0.014	0.0096	0.016	0.0099	0.011
Al (%)	Cu (%)	Co (%)	Mg (%)	Nb (%)	Ce (%)	W (%)	N (%)
0.023	0.0099	0.0074	0.0051	0.0057	0.08	<0.007	0.0076
Se (%)	Sn (%)	Zn (%)	As (%)	Bi (%)	Ta (%)	Fe (%)	
0.013	0.0083	0.021	0.0096	0.017	<0.010	99.5	

Table 2: Mechanical properties of galvanised iron

Material Property	Galvanized Iron
Density	7850 kg/m^3
Young modulus	200 GPa
Poison ratio	0.29
Yield strength	266 MPa
Hardness	64 HRB

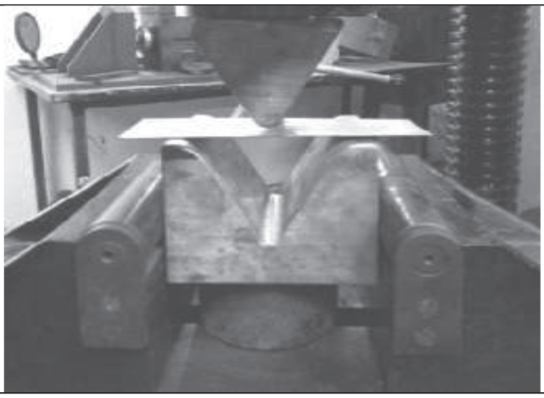


Fig. 4. V-die and punch set up in UTM

According to the process design, proper set of die and punch is first selected. Die is mounted between two clamps, one is movable and other is fixed to the key-slot. Die is kept above a cylindrical block. Punch is inserted on a cylindrical hole which is tightened by a screw. The sheets rest on die valley region extended equally from die end. Then punch is moved down until it touched upper surface of sheet. Hydraulic pump is started and allows the die to go up and made the sheet to bend according to die profile. This upward movement of die occurred smoothly. After reaching some distances, movement of die is made to stop, pump operation is interrupted and punch is allowed to trace back. This time appreciable amount of spring-back is noticed.

Keeping the die in the same position, the punch has been replaced with another suitable punch according to the process design. Amount of spring-back has been measured using a digital vernier height gauge. The parameters that are varied during the simulation are Die corner radius, r_i, Punch radius, r_p and material thickness, t. There are fourteen experiments that have been done for each type of material as the experiment set is designed according to response surface methodology (RSM). Coded values of process variables are shown in Table 3 and detail of experimental runs is given in Table 4.

Table 3: Coded values of R_p, R_d and t

Punch radius, R_p		Die corner radius, R_d		Thickness of sheet, t	
Value (mm)	Coded value	Value (mm)	Coded value	Value (mm)	Coded value
4	-1	10	-1	0.5	-1
8	0	15	5	1.0	0
12	+1	20	+1	1.5	+1

Table 4: Experimental data obtained

Sl. No.	Punch radius (mm)	Die corner radius (mm)	Thickness (mm)	Force (kN)	Spring-back (mm)
1	4	10	0.5	0.8	6.32
2	4	10	1.5	2	1.66
3	4	20	1.5	1.6	4.16
4	4	20	0.5	0.8	7
5	12	10	0.5	0.8	7.24
6	12	10	1.5	1.2	4.92
7	12	20	1.5	1.6	0.72
8	12	20	0.5	0.8	6.84
9	8	15	1	1.2	6.2
10	8	15	1	1.2	5.58
11	8	15	1	1.2	6.56
12	8	15	1	1.2	6.36
13	8	15	1	1.2	7.2
14	8	15	1	1.2	6.58

3. RESULTS AND DISCUSSION

Experiment is done on galvanized iron sheet of 150 mm length and 50 mm width. Thickness of three different values such as 0.5 mm, 1.0 mm and 1.5 mm is chosen for experimentation. Besides thickness, there are punch radius (R_p) and die corner radius (R_d) which are used as process parameters. Each of process parameters has three levels (low-moderate-high). Response surface methodology is used to design and analyze the results, obtained from the experiment. Bent GI sheet samples are shown in Fig.5.

Results obtained from the experiments are shown in Table 4. Values of spring-back and force requirement are tabulated and presented in terms of contour plot and surface plot as function of two process parameters at a time.

There is no fracture or any damage to the sheet during experiment. During trial, it is observed that there is no appreciable amount of spring-back when the sheet is bent up to full depth in die. This occurs due to different values of punch radius that does not match with different die valley geometry. Using trial and error method, a certain depth is chosen for each of the three die and punch sets and marking is made at that limit in each die with a scribe. It is observed that spring-back value is less for thick sheet and more for thin sheet. Die corner radius (R_d) has less influence on amount of spring-back as compared to punch radius (R_p). Die corner radius of 10 mm, punch radius of 12 mm gives maximum spring-back on a 0.5 mm sheet. Minimum spring-back obtained on a 1.5 mm sheet for die corner radius of 20 mm and punch radius of 12 mm. Requirement of force is observed to be independent of die corner radius. It mainly depends on punch radius and thickness of sheet. That is why there is only one set of contour and surface plot is shown typically.

Multiple regression equation has been found using MINITAB 17 software from the data obtained from the experiment. The relation of spring-back (Sb) with the Punch Radius (R_p), die corner radius (R_d) and thickness of sheet (t) is given in equation (1). These equations are generated by eliminating some terms such as (R_d*R_d) and ($t*t$) which do not have significant effect on the response. R-square value for this experiment is 90.05% that entails that the experimental observations are having fairly good correlation between the variables and the response although there are some deviations in the observed data.

Analysis of variance on the results obtained through spring-back experiments is done, and the outcome of the ANOVA is shown in Table 5. ANOVA table shows that F-value of sheet thickness, t (35.56) is much higher compared to any other variable/ factor than its table value (5.99). This indicates sheet thickness is having remarkable significance on spring-back effect. On the other hand, punch radius and die corner radius have no significant contribution on spring-back as their F values are lesser than F-table values. Similarly, 2-way interaction and interaction factors, (R_p* t) and (R_d* t) are not having any significance on spring-back, while Square term and (R_p* R_p), and the interaction term, (R_p* R_d) have are found to be having significance on spring-back. The model given by equation (1) is significant, but it is lesser than the Linear model. However, Lack of fit with F-value of 13.39 is also significant as it is more than F-value of 5.99 meaning that there are significant amount of data deviations from the modeled equation (1). Usually, 10% variation in experimental data is quite common and is considered acceptable as a rule of thumb. It appears that with this deviation of data also there is a large R-square value for this experiment of 90.05% indicating the experimental observations to have fairly good correlation between the variables and the response.

$$Sb = 6.413 + 0.072\ R_p - 0.177\ R_d - 1.993\ t - 1.556\ R_p * R_p - 0.972\ R_p * R_d - 0.118\ R_p * t - 0.247\ R_d * t \quad (1)$$

The contour plot and surface plot of spring-back (Sb) are shown with regard to punch radius (R_p), die corner radius (R_d) and thickness of sheet (t) in Fig. 6 through Fig. 11. Fig. 6 shows the contour plot and Fig. 7 the surface plot of spring-back with the variation of punch radius (R_p) and die corner radius (R_d) while sheet thickness, t is kept constant as 1 mm (coded value 0). It can be concluded from the plots that at the two extreme levels of punch radius, R_p changes in spring-back with die corner radius are quite significant. But two opposing natures are noticed. At lower value of punch radius, spring-back increases when die corner radius increases. At higher level of punch radius, spring-back gradually decreases with die corner radius. At the medium value of punch radius (coded value from -0.5 to +0.5), spring-back decreases with an increase in die corner radius. For a particular value of die corner radius, R_d spring-back first increases, reaches a maximum and then decreases with an increase in punch radius, R_p.

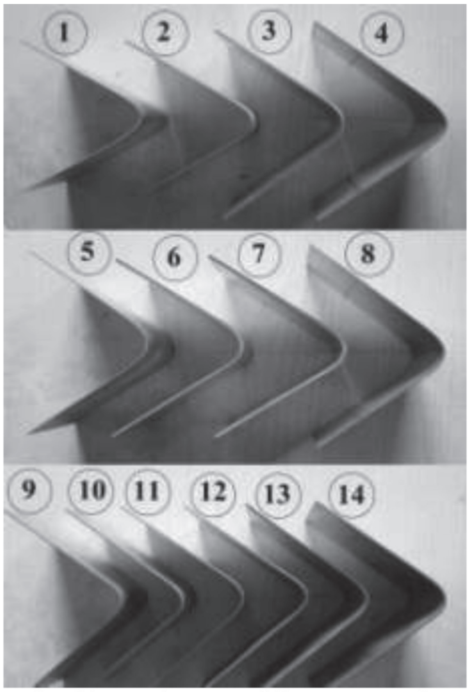


Fig. 5. Photograph of bent sheet at different experimental conditions

Table 5: Analysis of variance on observation of spring-back

Source	DF	Adj SS	Adj MS	F-Value	F table value
Model	7	48.5204	6.9315	7.76	4.21
Linear	3	32.0564	10.6849	11.96	4.76
R_p	1	0.0420	0.0420	0.05	5.99
R_d	1	0.2521	0.2521	0.28	5.99
t	1	31.7605	31.7605	35.56	5.99
Square	1	8.2993	8.2993	9.29	5.99
R_p*R_p	1	8.2993	8.2993	9.29	5.99
2-way interaction	3	8.1665	2.7222	3.05	4.76
R_p*R_d	1	7.5561	7.5661	8.47	5.99
R_p*t	1	0.1105	0.1105	0.12	5.99
R_d*t	1	0.490	0.490	0.55	5.99
Error	6	5.3590	0.8932		
Lack of fit	1	3.9480	3.9480	13.39	5.99
Pure error	5	1.4109	0.2822		
Total	13	53.8793			

As the contact length between sheet bottom surface and die valley increases, the frictional resistance to the sheet movement during sheet removal is also increased. When die corner radius is more, then contact between mating surface of die and sheet is more. As a result, it would give more resistance to the sheet and retards the movement. Spring-back also gets reduced. This may be the reason why large value of die corner radius usually gives less spring-back.

The influence of thickness of sheet (t) and die corner radius (R_d) on spring-back is shown in Fig. 8. In contour plot and surface plot, punch radius value is taken constant as 8 mm (0 level). From the contour plot, it is observed that spring-back mainly depends on thickness of sheet rather than die corner radius. With the change in die corner radius, spring-back does not change significantly at lower value of thickness, but at higher value of thickness, some change in spring-back is noticed. Spring-back value reduces at higher sheet thickness with higher die corner radius as observed from Fig. 8 and Fig. 9. The influence of thickness of sheet (t) and punch radius (R_p) on spring-back is shown in Fig. 10 and Fig. 11. In contour plot and surface plot shown, die corner radius value is constant as 15 mm (0 level). From the plot, it is observed that spring-back decreases with an increase in thickness of sheet, whereas spring-back increases up to a high level with the hike in punch radius and then decreases.

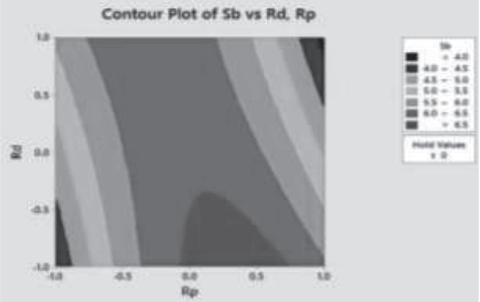


Fig. 6. Contour plot of spring-back with variation of punch radius and die corner radius at a constant sheet thickness of 1 mm (0 level)

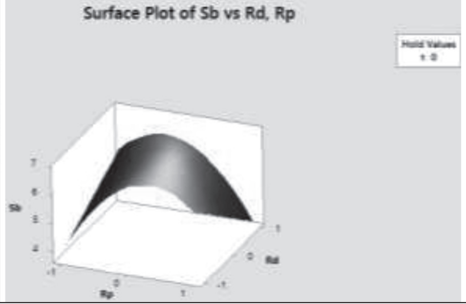


Fig. 7. Surface plot of spring-back with variation of punch radius and die corner radius at a constant sheet thickness of 1 mm (0 level)

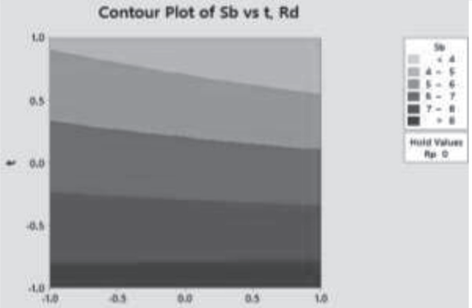


Fig. 8. Contour plot of spring-back with variation of die corner radius and thickness at a constant punch radius of 8 mm (0 level)

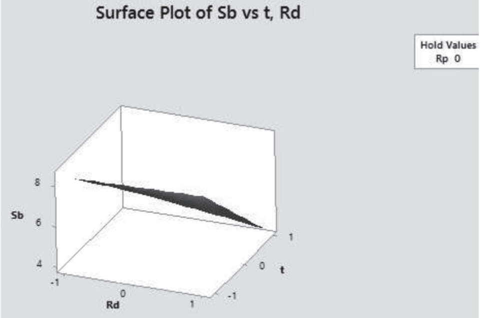


Fig. 9. Surface plot of spring-back with variation of die corner radius and thickness at a constant punch radius of 8 mm (0 level)

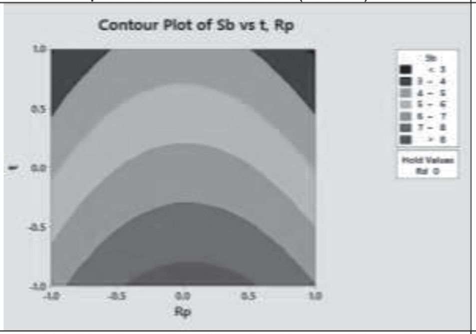


Fig. 10. Contour plot of spring-back with variation of punch radius and thickness at a constant die corner radius of 15 mm (0 level)

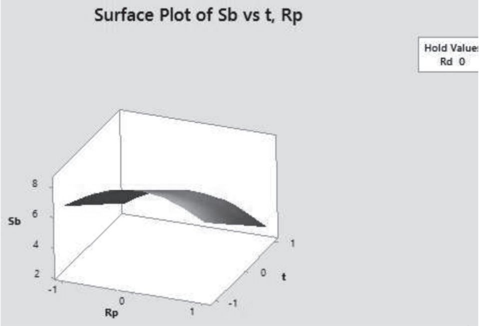


Fig. 11. Surface plot of spring-back with variation of punch radius and thickness at a constant die corner radius of 15 mm (0 level)

It is known that spring-back value is inversely proportional to flexural rigidity (EI, product of Young modulus and area moment of inertia). For a particular material, Young's modulus is the same but area moment of inertia depends on sheet thickness. As the sheet thickness increases, area moment of sheet also increases which in turn reduces spring-back. That may be the reason that thin sheet has more spring-back than thick sheet.

Fig. 12 and Fig. 13 typically show the variation of force requirement with punch radius (R_p) and die corner radius (R_d) at a constant sheet thickness of 1 mm (0 coded value). From these figures, it can be observed that force

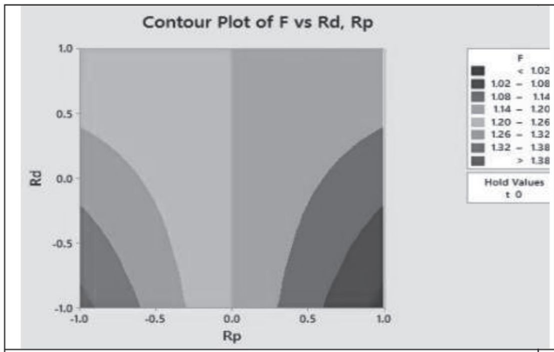


Fig. 12. Contour plot of force with variation of punch radius and die corner radius at a constant sheet thickness of 1 mm (0 level)

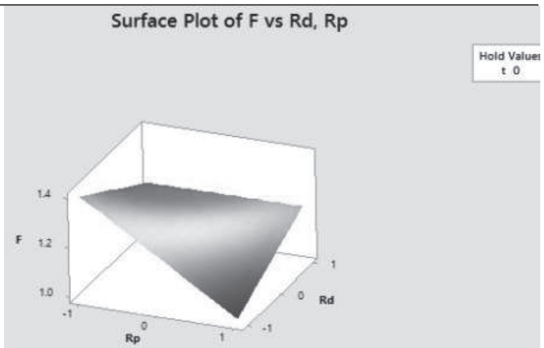


Fig. 13. Surface plot of force with variation of punch radius and die corner radius at a constant sheet thickness of 1 mm (0 level)

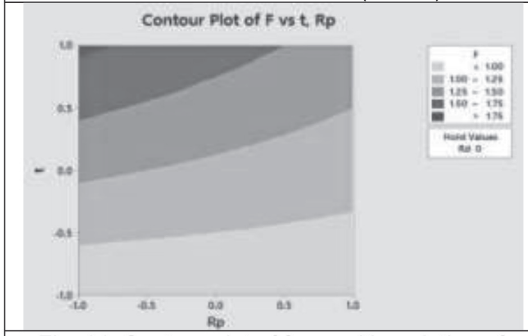


Fig. 14. Contour plot of force with variation of sheet thickness and punch radius at a constant die corner radius of 15 mm (0 level)

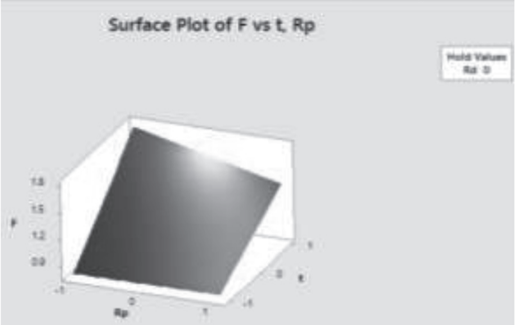


Fig. 15. Surface plot of force with variation of sheet thickness and punch radius at a constant die corner radius of 15 mm (0 level)

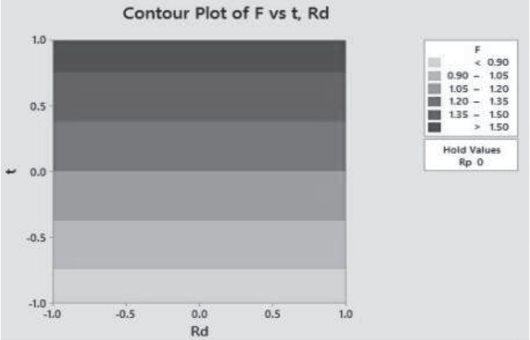


Fig. 16. Contour plot of force with variation of sheet thickness and die corner radius at a constant punch radius of 8 mm (0 level)

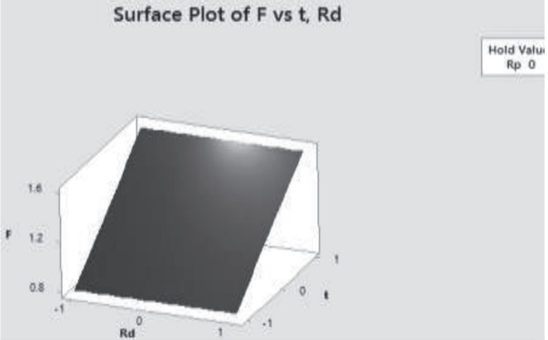


Fig. 17. Surface plot of force with variation of sheet thickness and die corner radius at a constant punch radius of 8 mm (0 level)

requirement decreases with an increase in punch radius. This decrement is much prominent at a lower value of die corner radius; however, at a higher value of die corner radius, force variation becomes marginal with a hike in punch radius. From the figures, it can be observed that there are two distinct zones based on punch radius value. Below a punch radius of 8 mm (0 level), force is compara-tively more and beyond 8 mm, force is relatively small. At the lower value of punch radius, force decreases as die corner radius increases. But force increases as die corner radius increases when punch radius is at higher level. Spring-back value is nearly 6 mm for galvanized iron sheet tested. It is known that spring-back is inversely proportional to young modulus of sheet material, and Young modulus E for galvanized iron is nearly 200 Gpa.

Effect of punch radius and sheet thickness on force requirement is shown in Fig. 14 and Fig. 15. Die corner radius value is taken as 15 mm constant (coded value 0). It is observed that force is directly proportional to thickness of sheet. However, at a higher value of punch radius, increment in force is relatively less. With the increment in punch radius, decrease in force value can be seen particularly at higher values of sheet thickness. Effect of die corner radius and sheet thickness on force requirement is shown in Fig. 16 and Fig. 17. Punch radius is taken as 8 mm (coded value 0). It is observed that there is no noticeable variation of requirement of force with the change in die corner radius. With the increase in sheet thickness, force values show proportional relationship due to increase in the area moment of inertia.

Spring-back value is directly proportional to bending moment and radius of curvature of sheet during bending. This radius of curvature is nothing but the radius of punch. With the increase in punch radius, bending moment of sheet gets reduced but the radius of curvature increases. When the coded value of punch radius is from -1 to 0, the rate of change of bending monent is more than rate of change of radius of curvature. That is why Spring-back value changes from some value to minimum value and opposite phenomenon is observed when coded value of Rp changes from 0 to +1. The explanation for thickness is the same as the above mentioned case.

With the observation made experimentally, appropriate strategy may be made based on the data obtained to make a product having suitable anglar bending portion, and there lies the importance of this experimental work.

4. CONCLUSION

In this work, spring-back of galvanised iron sheet material which is frequently used in industry and domestic purpose is taken into consideration. Effect of each process variable on spring-back is carefully studied and the following conclusions can be drawn:

- Thickness has more influence than two other variables on spring-back effect. Thin sheet gives more spring-back than thick sheet.
- Value of force requirement mainly depends on thickness of sheet. It is found that for a particular value of thickness, force requirement is less for higher punch radius and higher die corner radius.

- From ANOVA table, it is clear that influence of punch radius and die corner radius on spring-back is not significant if considered individually. But their combination has significant effect on spring-back.
- The experimental investigation reveals relation of some process variables on spring-back effect so that suitable design can be done to obtain typical amount of angular bend during manufacture of bent part.

REFERENCES

[1] Akkerman, R., Boogaard, A.H., Brekelmans, W.A.M., Geijselaers, H.J.M., Hu´etink, J., Meinders, T., Peerlings, R.H.J., de Rooij, M.B. and Schipper, D.J., Mechanics of Forming Processes, Lecture Notes, Graduate School of Engineering Mechanics, 2003.

[2] Marciniak, Z., Duncan, J.L. and Hu, S.J., Mechanics of Sheet Metal Forming, 2nd Edition, Butterworth-Heinemann Publication, 2002.

[3] Kuwabara, T., Asano, Y., Ikeda, S. and Hayashi, H., An Evaluation Method for Springback Characteristics of Sheet Metals Based on a Stretch Bending Test, IDDRG 2004, Forming the Future: Global Trends in Sheet Metal Forming, pp.55-64, Sindelfingen, Germany, 2004.

[4] Leu, D.-K., A Simplified Approach for Evaluating Bendability and Spring-Back in Plastic Bending of Anisotropic Sheet Metals, Journal of Materials Processing Technology, Vol. 66, pp.9-17, 1997.

[5] Zhang, D., Cui Z., Chen, Z. and Ruan X., An Analytical Model for Predicting Sheet Spring-Back after V-Bending, Journal of Zhejiang University Science, Vol. 8, No.2, pp.237-244, 2007.

[6] Morestin, F. and Boivin, M., On the Necessity of Taking into Account the Variation in the Young Modulus with Plastic Strain in Elastic-Plastic Software, Nuclear Engineering and Design, Vol. 162, No.1, pp.107–116, 1996.

[7] Narasimhan, N. and Lovell, M., Predicting Spring-Back in Sheet Metal Forming: an Explicit to Implicit Sequential Solution Procedure, Finite Elements in Analysis and Design, Vol.33, pp.29-42, 1999.

[8] Barlat, F., Banabic, D. and Cazacu, Anisotropy in Sheet Metals, The Fifth International Conference and Workshop on Numerical Simulation of 3D Sheet Forming Processes, Jeju Island, Korea, 2002, pp.515 – 524.

[9] Papeleux, L. and Ponthot, J.P., Finite Element Simulation of Spring-Back in Sheet Metal Forming, Journal of Materials Processing Technology, Vol.125, pp.785-791, 2002.

[10] Alves, J.L., Oliveira, M.C. and Menezes, L.F., Spring-Back Evaluation with Several Phenomenological Yield Criteria, 2nd International Materials Symposium, Vol. 455-456, Caparica, Portugal, 2004, pp.732–736.

[11] Gomes, C., Onipede, O. and Lovell, M., Investigation of Spring-Back in High Strength Anisotropic Steels, Journal of Materials Processing Technology, Vol.159, pp.91-98, 2005.

[12] Panthi, S.K., Ramakrishnan, N., Pathak, K.K. and Chouhan, J.S., An Analysis of Spring-Back in Sheet Metal Bending Using Finite Element Method (FEM), Journal of Materials Processing Technology, Vol.186, pp.120-124, 2007.

[13] Firat, M., Kaftanoglu, B. and Eser, O., Sheet Metal Forming Analyses with an Emphasis on the Spring-Back Deformation, Journal of Materials Processing Technology, Vol.196, pp.135-148, 2008.

[14] Thipprakmas, S. and Rojananan, S., Investigation of Spring-Go Phenomenon Using Finite Element Method, Materials and Design, Vol.29, pp.1526-1532, 2008.

[15] Wang, J., Verma, S., Alexander, R. and Gau, J.T., Spring-Back Control of Sheet Metal Air Bending Process, Journal of Manufacturing Process, Vol. 10, pp. 21-27, 2008.

[16] Bakhshi-Jooybari, M., Rahmani, B., Daeezadeh, V. and Gorji, A., The Study of Spring-Back of CK67 Steel Sheet in V-Die and U-Die Bending Processes, Materials and Design, Vol.30, pp.2410-2419, 2009.

[17] Eggertsen, P.A. and Mattiasson, K., On the Modelling of the Bending –Unbending Behaviour for Accurate Spring-Back Predictions, International Journal of Mechanical Science, Vol.51, pp.547-563, 2009.

[18] Yu, H.Y., Variation of Elastic Modulus during Plastic Deformation and Its Influence on Springback, Materials and Design, Vol.30, pp.846-850, 2009.

[19] Yilamu, K., Hino, R., Hamaski, H. and Yoshida, F., Air Bending and Spring-Back of Stainless Steel Clad Aluminium Sheet, Journal of Materials Processing Technology, Vol.210, pp.272-278, 2010.

[20] Dahlberg, M. and Segle, P., Evaluation of Models for Cyclic Plastic Deformation– A Literature Study, Inspecta Technology AB, 2010.

[21] Chatti, S., Effect of Elasticity Formulation in Finite Strain on Spring-Back Prediction, Computer and Structures, Vol.88, pp.796-805, 2010.

[22] Ouakdi, E.H., Louahdi, R., Khirani, D. and Tabourot, L., Evaluation of Spring-Back under the Effect of Holding Force and Die Radius in a Stretch Forming, Materials and Design, Vol.35, pp.106-112, 2012.

[23] Chogthairungruang, B., Uthaisangsuk, V., Suranuntchai, S. and Jirathearanat, S., Spring-Back Prediction in Sheet Metal Forming of High Strength Steels, Materials and Design, Vol.50, pp.253-266, 2013.

[24] Hakan, D., Mustafa, Ö. and Murat, S., Effects of Material Properties and Punch Tip Radius on Spring-Forward in 90° V Bending Processes, Journal of Iron and Steel Research, Vol.20, pp.64-69, 2013.

[25] Seo, Y.H., Park, J.W., Song, W.J., Kang, B.S. and Kim, J., Flexible Die Design and Spring-Back Compensation Based on Modified Displacement Adjustment Method, Advances in Mechanical Engineering, 2014.

[26] Lawanwomg, K., Hamaski, H., Hino, R. and Yoshida, F., A Novel Technology to Eliminate U Bending Spring-Back of High Strength Steel Sheet by Using Additional Bending with Counter Punch, Proceedings of the 11th International Conference on Technology of Plasticity, Nagoya, Japan, pp.957-962, 2014.

[27] Sayeed, G.M., Ahmed, H., Mohiuddin, M.V. and Sajid, S., Experimental Evaluation of Spring-Back in Mild Steel and Its Validation Using LS-DYNA, Proceedings of the 3rd International Conference on Materials Processing and Characterisation, pp.1376-1385, 2014.

[28] Choi, M.K. and Huh, H., Effect of Punch Speed on Amount of Spring-Back in U-Bending Process of Auto-Body Steel Sheets, Proceedings of the 11th International Conference on Technology of Platicity, Nagoya, Japan, pp.963-968, 2014.

[29] Krinninger, M., Opritescu, D., Golle, R. and Volk, W., Experimental Investigation of the Influence of the Punch Velocity on the Spring-Back Behaviour and the Flat Length in Free Bending, 48th CIRP Conference on Manufacturing Systems, pp.1066-1071, 2015.

[30] Balon, P., Światoniowski, A. and Szostak, J., Improved Method of Spring-Back Compensation in Metal Forming Analysis, Strength of Materials, Vol. 48(4), pp. 540-550, 2016.

[31] Sumikawa, S., Ishiwatari, A., Hiamoto, J. and Urabe, T., Improvement of Spring-Back Accuracy Using Material Model Considering Elastoplastic Anisotropy and Bauschinger Effect, Journal of Materials Processing Technology, Vol.230, pp.1-7, 2016.

[32] Zajkani, A. and Hajbarti, H., Investigation of the Variable Elastic Unloading Modulus Coupled with Nonlinear Kinematic Hardening in Spring-Back Measuring of Advanced High-Strength Steel in U-Shaped Process, Journal of Manufacturing Processes, Vol.25, pp.391-401, 2017.

[33] Phanitwomg, W. and Thipprakmas, S., FE-Analysis of Channel Width Effects on Spring-Back Characteristics in the U-Bending Process, Proceedings of the 17th International Conference on Sheet Metal, pp.17-22, 2017.

[34] Slota, J., Šiser, M. and Dvorák, M., Experimental and Numerical Analysis of Spring-Back Behaviour of Aluminium Alloys, Strength of Materials, Vol.49, 2017.

[35] Trzepiecinski, T. and Lemu, G.H., Effect of Computational Parameters on Spring-back Prediction by Numerical Simulation, Metals, Vol. 380, 2017