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Study of Coefficient of Friction and Springback Analysis of Brass in Bending at Elevated Temperature Conditions

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In the present work, finite element analysis is carried out for the minimization of springback in the V-bending process for high-strength brass sheet metal. Firstly, the uniaxial tensile test is conducted to determine the various material properties required for finite element analysis. The various test parameters considered in the V-Bending process are temperature (573 K, 673 K and 773K), punch speeds (1 mm/min, 5 mm/min and 10 mm/min), holding time (30 s, 60 s and 90 s) and sheet orientation concerning rolling direction RD (0^0), ND (45^0) and TD (90^0) for finite element analysis. The bending under tension test is used to determine the coefficient of friction at different temperatures and lubrication conditions, and these values are implemented in finite element simulations of the V-bending process. Taguchi analysis is carried out to determine springback of high-strength brass alloy by selecting four control factors (temperature, punch speed, holding time, and orientation). From the analysis of the signal-to-noise (S/N) ratio, it is reported that the temperature (46.93%) is the most significant parameter which influences the springback followed by holding time (26.29%), sheet orientation (24.07%) and punch speed (2.69%). The optimal set obtained for the minimum springback of brass alloy and the conformation test is performed at the optimum set conditions (773 K temperature, 1 mm/min punch speed, 90 s holding time, and 90° to the rolling direction of a sheet). With the optimal set of process parameters, Springback decreased significantly to around 68.68%. Through the investigation of springback analysis, it is directly proportional to the temperature and holding time and inversely proportional to the punch speed, but sheet orientation doesn't follow any trends.

Keywords: High Strength Brass Alloy, V-Bending; Springback, Process Parameters, Taguchi Analysis, Finite Element Analysis

1 Introduction

Brass is a substitutional alloy of zinc in copper. An increase in Zn content in Cu up to 45 wt.% results in better mechanical properties such as tensile strength & wear resistance, and upon exceeding 45 wt.% Zn strength deteriorates rapidly[1]. High-strength brass finds wide application in industries such as automobile, aerospace, nuclear, and home appliances[2].

Sheet metal forming is one of the most important, cost-effective and efficient parts-forming processes in which a sheet metal is formed into the desired shape with the help of appropriate form tooling. It is extensively used in the field of automobile, aerospace, nuclear, marine, and petrochemical industries[3].

Bending is one of the simple and easiest sheet metal forming operations in which the bent portion undergoes plastic deformation under the action of bending moment. The deformation behavior of the sheet metal depends on the material characteristics such as young's modulus, yield stress, the ratio of yield stress to ultimate tensile stress, and microstructure. The non-homogeneous strain of sheet metal at the bent portion crops the residual stress upon unloading, which results in the existence of the springback. It is expressed as a geometrical change (discrepancy in shape and dimension) from the desired (i.e. shape and dimensions). The magnitude of springback coefficient relies on the geometrical parameters, material parameters, process parameters, and technological parameters which include sheet thickness, orientation, tooling geometry, friction condition, lubrication condition, forming speed, and die temperature[4].

The magnitude of springback rises with cold working and heat treatment and also with a greater modulus of elasticity, yield strength or strain

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hardening of the material. Therefore, the springback of low strength material is smaller than that of high strength material. there are several methods available to minimize the springback like over bending, coining (bottoming the punch), stretch bending, and forming at elevated temperature[5].

The influence of the coefficient of friction on the springback value[6]. The elastic recovery of material causes the deviation of shape and dimension from desired formed part. Springback will present throughout and cannot be removed completely, but can minimize the elastic return of the formed component due to elastic recovery of sheet metal by suitable die design, and optimal setting of bending process parameters[7]. It is essential to consider the springback to produce high-quality parts with the economy to meet the demands of the market. The main objective of the mechanics of bending is to estimate the springback and bending forces precisely by strength and design analysis for the right section of form tooling to control the shape and dimension of the components[8]. Deviation of dimension from actual dimension leads to rejection in production due to the springback effect and hence to avoid this rejection of the component and qualify the part as acceptable, it is necessary to understand the springback behavior for that component[9].

In any manufacturing sector quality and productivity are primary problems for being competitive and surviving. Therefore, forming process should be novel, efficient, and cost-effective to solve these major issues and meet the goals of the manufacturing industry. Therefore, the estimation of springback in bending operation is of great significance[10]. Analysis of the bending process can be done by analytical techniques but is not sufficient to understand the influence of material and geometrical factors[11]. Though the experiments are expensive and time taking, they are required for the right understanding of the elastic recovery of materials. Various experimental tests were carried out to study the springback of sheet metals including U-bending[1], V-bending[12], cylindrical bending, three-point bending, rotary bending, and flanging. With the increase in sheet thickness, the radius of curvature, a ratio of the radius of curvature to sheet thickness leads to a decline in springback, and with an increase in bend angle, punch tip radius causes to rise in springback. Estimated the Threshold value for the transition of springback to springforward[13]. When sheet metal forming such as bending carried out at elevated temperatures results in improvement of formability, reduction in springback, and maximum force[14].

Friction is one of the key factor in sheet metal forming which dictates product quality and productivity and it has a vital role in assessing the properties of materials. If friction exists more than necessary, it harms the characteristics of a product. Various lubricants are used to reduce friction during the metal forming. There is a need to study the various factors affecting friction. Many researchers had worked on friction in many methods and the results were well documented in the scientific literature. But still, there is a lot to be explore about friction in sheet metal forming[15]. Friction is the most important parameter in bending operation. Friction evaluates the punch force and blank holder force during sheet bending. Friction dissipates some amount of the energy which is supplied to form the sheet metal. Friction plays a key role to find bending stress and strain in the sheet metal during forming. Hence, an understanding of friction and lubrication is essential to regulate the friction between the tool-work material interface[16].

Bending is one of the simple and most applied sheet metal forming operation for the production of lightweight and high-strength parts. In straight-line bending sheet metal deforms plastically in the bend region and not in the region away from the bend. To get the good quality parts perdition of springback and optimization is most crucial and important[17].

Taguchi's Design of experiments (DOE) is utilized to find the combined influence of various process parameters over desired output. To minimize springback, an optimal set of process parameters can be evaluated by computing the signal-to-noise (S/N) ratio, and the individual influence of process parameters over springback can be determined with the help of analysis of variance (ANOVA). Zhang *et al.*[18] presented the effect of Young’s modulus on the springback for an aluminum alloy in the U-bending. Ramadass *et al.*[19] selected the sheet thickness, die opening and punch radius as the process parameters for titanium grade 2 material and, based on Taguchi (L9) orthogonal array, reported the sheet thickness to be the most influential parameter on springback.

Bakhshi *et al.*[20] considered CK67 steel sheets for V-bending and observed sheet thickness to be the most affecting parameter for springback. Zong *et al.*[21]

investigated a titanium alloy (Ti–6Al–4 V) in the V-bending process by understanding the effect of holding time and punch radius over spring-go (forward) and springback effects within different temperature ranges (RT to 850 °C).

Thipprakamas *et al.*[22] computed ANOVA and Taguchi analysis in the V-bending process of aluminum (A1100) for studying the effect of punch radius, material thickness and bending angle on spring-go and springback. Verma *et al.*[23] studied the influence of anisotropy and observed that springback raised with anisotropy of sheet metal.

Panthi *et al.*[24] developed and employed an FEA algorithm, namely total-elastic–incremental-plastic (TE–IP) for V-bending of aluminum sheets and observed friction to be the least influential parameter over springback.

Thipprakamas *et al.*[25] studied the phenomenon of springback and spring-go in the V-bending process for aluminum (A1100) using FEA. Forcellese *et al.*[26] analyzed the springback effect in V-bending by using FEA, in which they considered the loading step as explicit and the unloading step as implicit analysis and observed punch nose radius to be the most influential parameter.

Saxena *et al.*[27] studied the parametric optimization in welding to find out the suitable parameter set. KK Saxena *et al.*[28] presented the study over the biodegradable implant materials. KK Saxena *et al.*[29] reported the analysis of magnesium-based metal matrix prepared by powder metallurgy.

From an extensive literature review, it has been noticed that much work had been done for the analysis of springback behavior for traditional metals such as titanium, steel and aluminum. However, no efforts have been made to understand the characterization of the friction coefficient and springback behavior of high strength brass.

Hence, in the present research work, the study of the coefficient of friction and springback behavior of high-strength brass in V-bending has been carried out with the aid of Taguchi's design of the experiment ($L_{27}3^4$ orthogonal array) which consists of four control factors (temperature, punch speed, holding time, rolling direction) and three levels. S/N ratio and ANOVA analysis are carried out to find out the optimal set of parameters and most significant parameters for springback. FEA is carried out using user-defined material (UMAT) subroutine in ABAQUS 6.13 software for the validation of experimental results.

2 Materials and Methods

2.1 Material Composition

Chemical composition analysis was carried out by the Optical Emission Spectroscopy with ASTM E478 standard to evaluate parent brass sheet metal and list as in Table 1.

2.2 Microstructure

Microstructure evaluation of parent brass sheet metal was carried out as per the ASTM E3-95 standards. Microstructure reveals that it consists of alpha and beta matrix. The initial microstructure of the parent brass sheet metal is as shown in Fig. 1.

2.3 Experimental Details

2.3.1 Tensile Test

In the present work, high-strength brass was cold-rolled to 1 mm thickness and uniaxial tensile test specimens were made as per the sub-sized ASTM E08/E8M-11, by machining under the wire cut EDM with the gauge length of 30 mm, 21 mm width and 1 mm thickness. Uniaxial isothermal tensile tests have been performed at a temperature of 300 K to 773 K under a constant quasi-static strain rate (0.001, 0.01, and $0.1s^{-1}$) with different sheet orientations (0^0, $45^{0,}$ and 90^0). The experiment was performed by BISS Electra Servo Electric 50 KN loading capacity, computer-controlled universal testing machine (UTM) under quasi-static straining conditions. It is equipped with a two-zone split furnace, with a maximum 1000 ºC heating capacity with ± 3 °C accuracy, temperature of the specimen was controlled through 3 thermocouples.

Table 1 — Chemical composition of Brass sheet metal

Element	Zn	Pb	Fe	Cu	IMP
% in wt	Bal	0.292	0.1	64.305	0.6

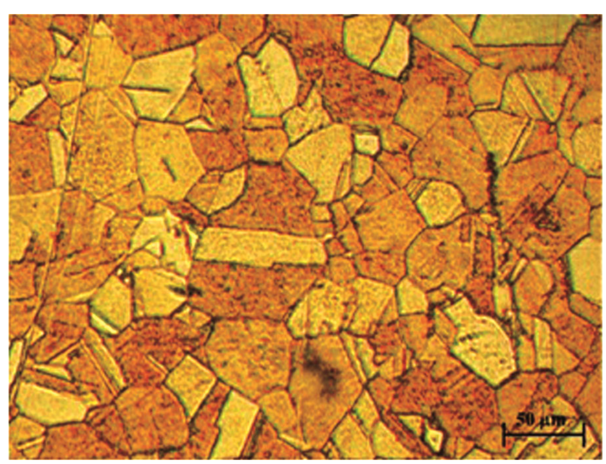

Fig. 1 — Initial Microstructure of parent Brass sheet metal.

Mechanical properties are determined experimentally by using empirical equations (Hollomon and Swift), which are reported in the listed Table 2.

Estimation of Anisotropy: The robust stress-based parameters namely in-plane anisotropy (A_{IP}) and the anisotropic index (δ) are estimated as the equations 3 and 4 presented below. In-plane anisotropy (A_{IP}) and anisotropic index (δ) values are reported in Table 3.

$$A_{IP} = \frac{2\times\sigma_{ys}^{0}-\sigma_{ys}^{90}-\sigma_{ys}^{45}}{2\times\sigma_{ys}^{0}} \quad \ldots (3)$$

where, σ_{ys}^{0} , σ_{ys}^{45} , σ_{ys}^{90} are yield strength at 0°, 45° and 90°orientation of sheet metal.

$$\delta = \frac{(\%El)^{0}-(\%El)^{90}}{(\%El)^{0}+(\%El)^{90}} \qquad 0 \le \delta < 1 \quad \ldots (4)$$

where, (%El)° and $(\%El)^{90}$ are % elongation at 0° orientation and 90° orientation respectively.

2.3.2 Bending Under Tension (BUT) Test

The Bending Under Tension (BUT) test is currently the most commonly used test. The BUT test consists of bending a strip of the sheet through a predetermined radius pin and sliding the sheet over it. To do this, a force is applied to one end of the sheet to provide relative movement between the sheet and the pin. At the other end, a back tension force is applied to bend the sheet over the pin and the contact pressure on the pin can be varied.

In this test, there are two forces required to make the sheet slide over the pin, one is the frictional force in the interface (inner surface of the test specimen and outer surface of the pin) and the other is the force required to perform the sheet bending. The purpose of the test is to know the frictional force between the contact surfaces. The force required to make the sheet move is then the bending force plus the frictional force.

The coefficient of friction can be determined by bending and pulling a brass sheet strip over a cylindrical pin by bending under a tension test. A cylindrical pin of 25 mm diameter made up of Inconel 718 material is acting as a die over which the specimen has to slide to a specified rubbing length in a definite bend angle. A constant back tension force of approximately 90% of the yield strength was applied during the test. Specimens in the form of strips (500 mm length, 30 mm width, and 3 mm thickness) were prepared as per the ASTM standard using wire cut EDM from the parent brass sheet in all three directions RD (0^0), ND (45^0), TD (90^0). Bending under tension test was carried out under the specified test parameters such as a temperature of 300 K, 573 k, 673 k, and 773 k, bend angle of 0^0, $41.8^{0,}$ and 67^0, sheet orientation of RD (0^0), ND (45^0), TD (90^0) and lubrication of dry, molykote and plastic at a fixed sliding speed of 4 mm/min over a constant sliding length of 10 mm. The obtained experimental results were presented in Table 4 listed below. In addition to its computerized control, this machine can reach a peak temperature of 1500°C with an accuracy of 10°C. During the friction tests, the temperature of the specimen was controlled using an electronic pyrometer and a Dynatherm controller.

Table 2 — Equations for empirical stress-strain relationships.

Hollomon Equation $\sigma = k_1 \varepsilon^{n_H}$ … (1)
Swift Equation $\sigma = (\varepsilon + k_s\,(\varepsilon_0)^{n_s})$ … (2)

3 Result and Discussion

3.1 Finite Element Analysis of V-bending

Numerical simulations were performed for all 27 experiments using the same set of process parameters as mentioned in Table 5. User-defined material (UMAT) subroutine was incorporated in numerical solver ABAQUS 6.13 for FEA. The die and punch were modeled using a discrete rigid type, in which a rigid body reference node controls the whole movement. R3D4 type of mesh elements was used. The deformable blank was meshed using S4 mesh element which is a 4-node shell element used for thin sheet

Table 3 — Average mechanical properties of Brass sheet

Temperature	Orientation	YS (MPa)	UTS (MPa)	% Elongation	In-plane Anisotropy (A_{IP})	Anisotropy index (δ)
300K	0º	305	404	30	0.07213	0.0909
	45º	290	380	29		
	90º	276	369	25		
573K	0º	293	354	36	0.07167	0.0746
	45º	271	341	32		
	90º	273	341	31		
673K	0º	184	202	39	0.07065	0.06849

Table 4 — Experimental friction characterization of the Brass sheet with Inconel 718 pin at different temperature conditions.

Bend Angle	Interface Condition		Temperature (K)			
			300 K	573 K	673 K	773 K
0^0	Without Lubrication	Dry	0.30±0.07	0.33±0.03	0.34±0.02	0.35±0.08
	With Lubrication	Plastic	0.24±0.06	0.25±0.05	0.26±0.04	0.27±0.04
		Molykote	0.31±0.03	0.32±0.07	0.32±0.07	0.33±0.02
41.8^0	Without Lubrication	Dry	0.51±0.04	0.53±0.08	0.55±0.03	0.57±0.04
	With Lubrication	Molykote	0.34±0.02	0.41±0.05	0.46±0.07	0.47±0.06
		Plastic	0.35±0.09	0.39±0.03	0.51±0.06	0.44±0.08
67^0	Without Lubrication	Dry	0.50±0.08	0.51±0.06	0.52±0.04	0.53±0.07
	With Lubrication	Molykote	0.41±0.07	0.43±0.04	0.44±0.06	0.46±0.03
		Plastic	0.37±0.06	0.42±0.7	0.44±0.05	0.43±0.04

Table 5 — Mesh sensitivity analysis

Mesh Description	Simulation results	
	Springback angle	CPU run-time (s)
Uniform mesh with size 5 × 5 mm^2	61.18^0	1934
Uniform mesh with size 2.5 × 2.5 mm^2	61.520	3528
Uniform mesh with size 1 × 1 mm^2	1.270	7531
Mesh with size 1 mm over blank and 0.4 mm near the fillet region	60.560	9418

Table 6 — Control factors and their levels

Level / Parameter	Level 1	Level 2	Level 3
Temperature	303K	573K	673K
Punch Speed	1 mm/min	5 mm/min	10 mm/min
Holding Time	30 sec	60 sec	90 sec
Rolling Direction	RD (0^o)	TD (45^o)	ND (90^o)

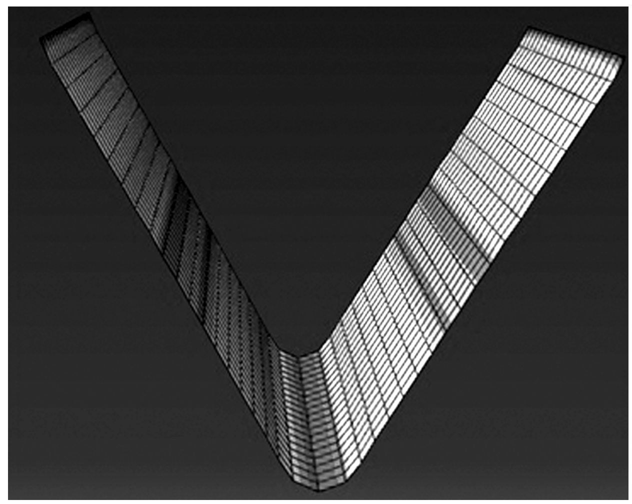

Fig. 2 — FEA simulation with optimized parameter setting for loading step.

analysis. FEA simulation with optimized parameter setting for loading step presented in Fig. 2.

3.2 Analysis of the Taguchi Technique

The phenomenon of springback plays a vital role in sheet metal forming processes. Control factors, namely temperature, punch speed, holding time, and rolling direction, were selected for analysis of springback by $L_{27}(2^4)$ orthogonal array. The control factors and their levels were presented in Table 6. The mean angle of the V-bend in each specimen is evaluated using Fig. 3 and is stated in Equation 5. In Equation 5, θ_1 and θ_2 are the angles of the inner and outer faces of the V-bended sheet. Three different specimens were taken for each set of process parameters and their average angles. The average springback angles are reported in Table 7 and shown in Fig. 3. The values of the S/N ratio were reported in Table 7.

Taguchi analysis was carried out by two measures, namely target performance measure (TPM) and noise

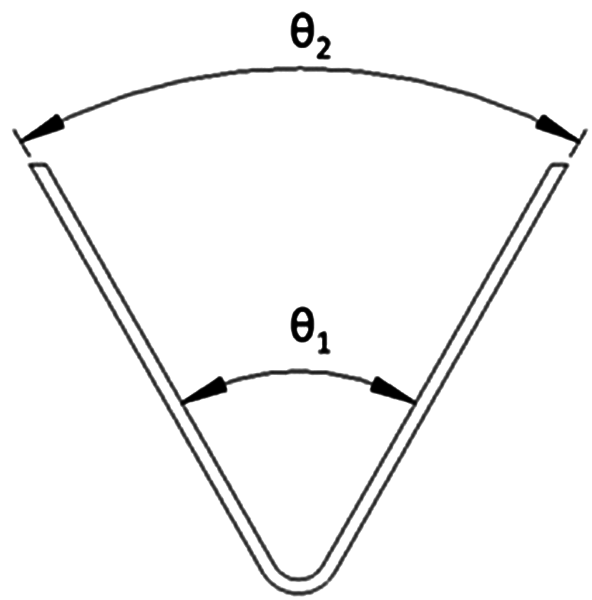

Fig. 3 — Springback angle calculation.

Table 7 — Formulation of L_{27} (3^4) orthogonal array for Springback angle and S/N ratio

Run	Temperature (K)	Punch Speed (mm/min)	Holding Time (sec)	Rolling Direction (^{0})	Average Angle (θ_f)	S/N Ratio
1	573	1	30	0	61.34	-36.54
2	573	1	60	450	61.54	-36.51
3	573	1	90	900	61.58	-36.28
4	573	5	30	450	61.01	-36.57
5	573	5	60	900	61.85	-36.36
6	573	5	90	0	61.24	-36.32
7	573	10	30	900	61.38	-36.49
8	573	10	60	0	61.42	-36.44
9	573	10	90	450	61.01	-36.4
10	673	1	30	0	61.31	-36.16
11	673	1	60	450	61.18	-36.19
12	673	1	90	900	61.02	-36
13	673	5	30	450	61.02	-36.26
14	673	5	60	900	61.74	-36.05
15	673	5	90	0	61.96	-36.05
16	673	10	30	900	60.89	-36.12
17	673	10	60	0	60.76	-36.08
18	673	10	90	450	60.45	-36.12
19	773	1	30	0	60.99	-35.91
20	773	1	60	450	60.74	-35.91
21	773	1	90	900	60.43	-35.77
22	773	5	30	450	61.12	-35.94
23	773	5	60	900	60.99	-35.81
24	773	5	90	0	61.08	-35.8
25	773	10	30	900	60.05	-35.85
26	773	10	60	0	60.16	-35.84
27	773	10	90	450	60.25	-35.81

performance measure (NPM)[30,31]. NPM aids in the selection of a set of process parameters which decreases the variation in desired output values, and it does not influence the mean value at all. The S/N ratio is taken for analysis of NPM. Mean responses are frequently taken in TPM analysis. Mean responses are the average values of all the measures considered (three in the present case) for a set of parameters. The governing parameters of NPM are known as variability process parameters, while the governing parameters of TPM are known as target process parameters.

Analysis of variance (ANOVA) is a statistical approach that is utilized to compare the performance of each considered process parameter. It also gives a quantitative comparison, i.e., the percentage contribution of each process parameter which helps in selecting the most significant parameter on the springback effect. The ANOVA table according to TPM analysis is represented in Table 8. In the analysis of TPM, temperature (warm forming condition) had the greatest contribution toward minimizing the springback followed by holding time, rolling direction or sheet orientation, and punch speed for high-strength brass alloy. High-strength brass becomes soft with temperature rise and hence formability improves and retains the deformed form easily.

Table 8 — ANOVA for TPM (Mean Springback Response)

Source	Seq. SS	P Value	% Contribution
Temperature	85.056	0.029	73.06
Punch Speed	03.060	0.653	02.63
Holding Time	15.004	0.007	13.05
Rolling Direction	11.926	0.008	11.26
Total	115.046	-	100

Based on observation from Fig. 4, springback decreases with temperature rise. The holding time upon loading in V-bending also plays a major role in minimizing the influence of springback as reported in Fig. 4. The orientation of sheet metal also has a significant contribution to the springback effect, which is presented in Fig. 4, and also a variation of the springback angle with the sheet orientations. The highest springback is reported when grain orientation with the punch is at 45° (ND) followed by 0° (RD) and 90° (TD). However, in the present study, punch speed being a process parameter was found to be the minimum and negligible effect on springback[32,33]. The

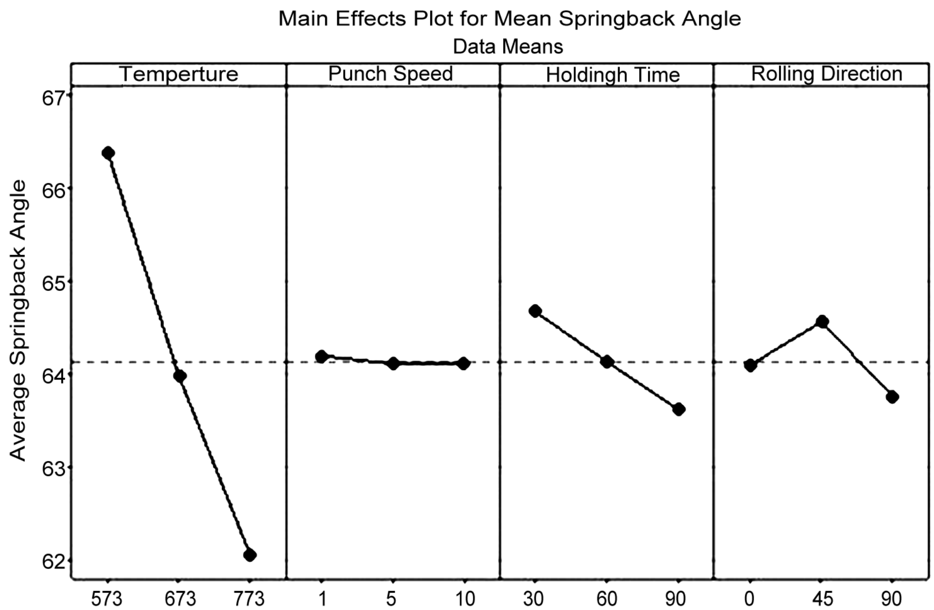

Fig. 4 — Main effect plot for mean springback angle.

level of process parameter having a lower average springback angle is always preferred. Table 9 depicts the ranking of process parameters as per their contribution to minimizing the springback effect. From the response Table 9, it was clear that the temperature was the most significant parameter in minimizing the springback followed by holding time, sheet orientation, and punch speed. Statistically, it is equally important to find the interaction between each parameter and the obtained response called the *p*-value, which is depicted in Table 8. The significance level considered for *p*-value analysis is 0.05 (5%). Parameters having a *p*-value lower than the significance level considered for the present study (i.e., 0.05) are more statistically affecting the investigation[29,30].

In the present work, temperature (0.3%), holding time (0.6%), and rolling direction (0.7%) have greater relevance than punch speed (64.8%) in minimizing the springback effect.

From ANOVA as NPM reported in Table 10, temperature, holding time and rolling direction have a greater influence in maximizing the S/N ratio than the punch speed. Based upon the delta value in the response table for NPM, as depicted in Table 11, a rank was attributed to the parameters that contribute to a rise in the S/N ratio. Hence, the temperature has a greater influence followed by holding time, rolling direction, and punch speed in the case of NPM.

NPM analysis was performed to recognize the process parameter set that aids in reducing the variation in output response. S/N ratios are determined based on 'smaller is better' in MINITAB software as the aim is to minimize the springback[12]. The S/N ratios are determined based on Equations 6 and 7. According to the determined S/N ratio for every run, experiment 21 (temperature = 773 K, punch speed = 1 mm/min, holding time = 90 s and

Table 9 — Response table for TPM

	Temperature	Punch Speed	Holding Time	Rolling Direction
Level 1	6.37	4.19	4.67	4.09
Level 2	3.97	4.11	4.13	4.56
Level 3	2.06	4.11	3.61	3.76
Delta	4.31	0.08	1.05	0.80
Rank	1	4	2	3

Table 10 — ANOVA for NPM

Source	Seq. SS	P Value	% Contribution
Temperature	192.217	0.012	46.99
Punch Speed	11.971	0.977	2.63
Holding Time	108.131	0.011	26.36
Rolling Direction	99.062	0.076	24.02
Total	411.381	-	100

Table 11 — Response table for NPM

	Temperature	Punch Speed	Holding Time	Rolling Direction
Level 1	-36.44	-36.15	-36.21	-36.13
Level 2	-36.12	-36.13	-36.14	-36.20
Level 3	-35.86	-36.13	-36.07	-36.09
Delta	0.58	0.01	0.14	0.11
Rank	1	4	2	3

Table 12 — Optimum settings for each process parameter

Process Parameter	TPM		NPM		Selected Level	Actual Value
	Level	% Contribution	Level	% Contribution		
Temperature	3	73.12	3	47.12	3	773 K
Punch Speed	1	2.63	3	2.61	1	1 mm/min
Holding Time	3	13.01	3	26.13	3	90 s
Rolling Direction	3	11.24	3	24.14	3	90^0

sheet rolling direction = 90°), as reported in Table 7, has the greater S/N ratio and thus it can be treated as the most optimal setting for minimizing springback in the present work. However, an additional validation test was conducted.

$$\theta' = \frac{(\theta 1 + \theta 2)}{2} \quad \dots (5)$$

$$\frac{S}{N} = -10 \text{ X } \log_{10} (y^{-2}) \quad \dots (6)$$

$$\bar{y} = \sum_{i=1}^{n} \frac{y_i}{n} \quad \dots (7)$$

Various process parameters were considered for the validation test based on their relative contribution to minimizing the springback effect. Based on the percentage contribution of each process parameter in TPM and NPM analysis the condition for pooled and not pooled is computed. In the present work, the condition for pooling is taken to be 5%. The effect of each particular factor has on the relative contribution of NPM and TPM analyses is depicted in Table 10. In the punch speed case, TPM (2.63%) and NPM (2.61%) contribution is less than 5%; hence, it is decided to be pooled. Conversely, if a process parameter is not pooled in either NPM or TPM analysis, then those factors are considered to have the most significant contribution in minimizing springback, such as temperature, holding time of blank and rolling direction. Among NPM and TPM, whichever is having the highest percentage contribution toward minimizing springback is taken for further analysis in the confirmation test.

The optimal set of control factors (process parameters) for the test was as follows: temperature = 773 K, punch speed = 1 mm/min, holding time = 90 s, and rolling direction = 90°. The confirmation test was conducted three times, and springback results are reported in Table 12.

4 Conclusion

The main conclusions reported from the present study are:

- Various sheet metal properties such as yield and ultimate strength are significantly influenced by the deformation rate, the orientation of the sheet, and test temperature.
- From the bending under tension test, it is clear that the coefficient of friction value decreases with lubrication and molykote is most effective when compared with plastic.
- According to ANOVA for means and *S/N* ratio on the springback, it is clear that temperature is the most significant parameter followed by holding time, rolling direction, and punch speed.
- Upon confirmation test by utilising the optimal set (a temperature of 773 K, punch speed of 1 mm/min, holding time of 90 s, and sheet orientation of 90°), it is observed that around 69.68% springback value is declined.
- It is reported that Springback is inversely proportional to temperature and holding time but directly proportional to the punch speed. No distinct relationship between sheet orientation and springback angle.

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