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Study the Effect of Stretching Force and Speed on the Induced Spring-Back of Aluminum AI6061

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ABSTRACT

Controlling Spring-Back (SB) is the key concern of the sheet-metal forming (SMF) manufacturing. Phenomenon of the SB is one of the most important defects of the SMF processes. It can be defined as the product diffraction from the designed dimension after the removal of the effective forming force. In stretching of sheet metal process associated with the SB phenomenon, two types of forces are normally applied, one of them is a stretching with tensile force (pre-stretching process) and the other one is without tensile force (post-stretching process). The stretching speed (strain rate) is also an important factor affecting the completion of the forming process. In this work, the effect of both stretching speed and stretching force on the stretching behavior in terms of SB occurrence were studied in (2) kinds of stretch forming procedure (pre-stretching and post-stretching) achieved experimentally by testing 78 test samples of Al 6061 alloy sheet. Tests were experimentally conducted utilizing a die having a V-shape for stretching the sheet at (2) chosen levels of stretching speed and force and speed as well as in accordance to the matrices of the design prepared via employing Design of Experiment (DoE) software (Design Expert version 10). SB of the stretched sheet was measured experimentally after the stretching processes for the optimization purpose. ANOVA statistical analysis was used to check the adequacy of the resulted models with 95% confidence level. Results display that growing the put up-stretching force correctly reduces the spring-again perspective, with a decrease of as much as 44.1% within the SB attitude while hot dies have been utilized in assessment to bloodless dies, which done only a 9.7% reduction when the blank temperature improved from 20°C to 450°C. The findings additionally indicate that the SB quantity decreases with the optimization of the procedure parameters, improving the general dimensional accuracy of the final components. Two mathematical models were established via the technique of response surface methodology (RSM) and manifested that the stretching force influence is greater than the stretching speed effect. Also, a comparison was conducted between the experimental and theoretical results of the two types of stretching process at the optimum conditions of each process.

1. INTRODUCTION

1.1 SMF

SMF is a process of transforming the needed form geometry. In such process, a certain sheet metal is converted into a beneficial component with an intricate geometry. The process of stretch forming was evolved as an approach of placing the sheet metals beneath a combination of axial tensile and bending stresses at the similar period. Occasionally, a component bending before can be utilized as a starting material for stretching by drawing. In the process of stretch forming, the sheet is fastened around its edges as well as stretched above a die or a forming block. Such method strains the metal after the limit of elasticity for permanently setting the form of the work-part shape. The work-parts may possess one or two curvatures, such as in the structure's frames and the airplane's skin panels, or the body components of the vehicle. The highly significant challenge for the automotive manufacturing in the future is to satisfy the request of decreasing the consumption of fuel with a concurrent increment of the protection characteristics via aluminum (Al) alloys that can be shaped into components via a diversity of procedures alike to those utilized for the steels.

Pre-stretching forming procedure of a sheet-metal blank (SMB) is conducted utilizing the secondary hydraulic jack of the machine to reach a point close to the limit of yielding, as well as the chief hydraulic jack begins forming the blank until attaining the eventual limit for its movement, by which the hydraulic governor retains the generated forces via two jaws fixed via governing the oil pressure. Beyond attaining the eventual limit, these two jaws begin to accomplish this stretching procedure for approaching the needed plasticity limit, as evinced in Figure 1.

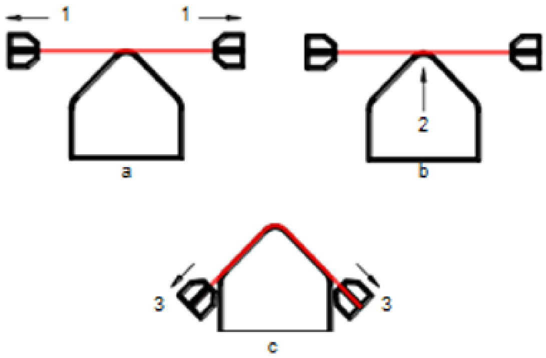


Figure 1. The pre-stretch forming process

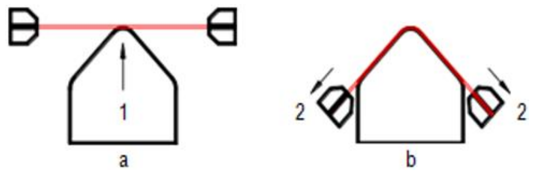


Figure 2. The post-stretch forming process

While the post-stretching forming process of the SMB is alike the pre-stretching forming process, it begins without the stretching force in the jaws, as manifested in Figure 2.

1.2 SB in SMF

One of the most important SMF processes is a stretching employed in aerospace manufacturing; such a method is chiefly utilized for producing the parts of the skin, like the leading edge of a wing. The principles of stretch stretch-forming process start by clamping the sheet on both sides with a gripper. Then, this sheet is draped about a die via shifting grippers toward each other and the final shape is achieved by stretching the sheet around the die. And, in such a manner, precisely formed products can be achieved with minimum SB. As well, single as doubly curved products can be produced with this process. The technological development in SMF is resulted from the requirement for an increase in the production and the accurateness of the formed parts. Execution of such processes is likely owing to the enhancements of automation, technological processes computerization, and forming tools. In this process, the sheet metal is subjected to complex deformation load such as stretch with bending load, but when the load is removed, the SB phenomenon will happen, this phenomenon leads to inaccurate final dimensions, as shown in Figure 3 [1].

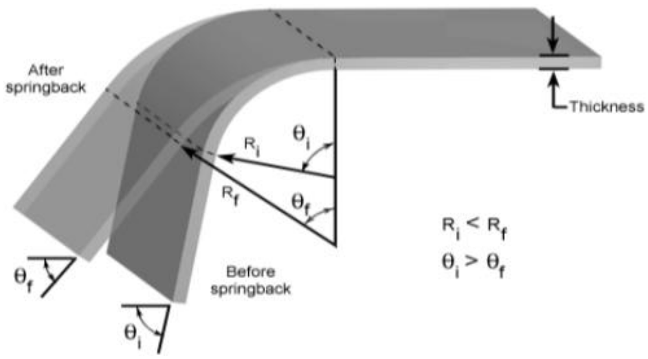


Figure 3. A 3D view of the SB effect of sheet metal forming [1]

SB postures a severe difficulty through the SMF procedures design owing to problems in determining the precise form and the dimensional accurateness of stamped parts. The SMB forming with preheating is a technique to prevent the influence of SB. Nevertheless, such a solution includes the increase of cost resulting from the conventional process of the heating of material as well as the material safety need against oxidation.

If a metal is being deformed into the zone of plastic, the entire strain comprises Figure 2 portions, the elastic portion as well as the plastic portion. And, when eliminating the load of deformation, a decrease in stress will take place and consequently the entire strain will reduce via the elastic portion quantity, which causes the SB. The interest in SB as an investigation field and the used area is considerable and is rising fast. Many research studies conducted previously highlighted the significance of SB in the production activities and proposed methods for reducing such perpetual physical change. And, the normal point of the whole such research investigations is that they tried to estimate the SB quantity, consequently designing, and then the stage of production. So, recognizing earlier the SB quantity possesses a cardinal significance. The SB changes with the composition, properties of the material, and the dimensional thickness and outer diameter range. It's needed to govern the SB for achieving precise dimensions. Nevertheless, the SB has to be homogenous and has to drop within the satisfied limits of tolerance. The SB results in a deviation from the designed form of the target, downstream amount difficulties, and assembly problems. The optimization is obtaining a substitute with the highly price active or uppermost performable effectiveness beneath certain constraints, via the maximization of the wanted parameters and the minimization of the unwanted ones.

SB control is too significant, particularly in the lightly curved sections like the bottom of the stamping, and the SB is reduced if the tension is adequate to reason tensile yielding across the entire cross section [2].

1.3 Previous research works

1.3.1 Optimization techniques in stretch forming

He et al. [3] optimized cold stretch forming for plane titanium-alloy skins to limit spring-lower back (SB), imparting hints for SB manipulation.

Fei et al. [4] focused on variable pressure in stretch forming, displaying how adjusting forces can reduce SB more successfully than regular pressure.

Ma et al. [5] explored rotary stretch bending for aluminum alloy profiles, showing that growing stretching strain decreased SB and stepped forward dimensional accuracy.

These studies agree that optimization of system parameters (e.g., forces, stretching amounts) is prime to minimizing SB and enhancing the accuracy of the shaped parts.

Further studies are needed to explore how special fabric kinds and forming strategies may be optimized in diverse commercial programs.

1.3.2 Material properties impact on SB

Arunkumar et al. [6] examined how fabric properties like yield electricity, modulus of elasticity, and pressure hardening impact SB in stretch metal forming (SMF).

Li et al. [7] furnished a systematic overview of the spring-lower back behaviors of titanium sheets, emphasizing how excessive-stress-fee forming reduces SB.

Liu et al. [8] confirmed that increasing temperature reduces energy and Young's modulus ratio in Ti-6Al-4V, which in flip decreases the SB.

All research spotlights the extensive role material houses (e.g., yield power, strain hardening, modulus of elasticity) play in SB conduct, agreeing that accelerated temperatures usually reduce SB.

While temperature control and fabric houses are studied, similarly exploration into alternative substances, especially composite ones, is still missing. Can novel materials like alloys with better elastic residences notably outperform modern materials in minimizing SB?

1.3.3 Numerical and simulation-based methods

Sasaki et al. [9] used finite element method (FEM) to are expecting SB in Al2024-T3 and Al7075-T6 sheets, showing strong alignment among experimental and simulation outcomes.

Pourboghrat and Chu [10] proposed a version to expect SB the use of moment-curvature relationships, established with FE simulations.

Fei et al. [4] hired support vector regression (SVR) to expect SB and proven higher accuracy than artificial neural networks (ANNs).

All studies validate FEM and SVR as reliable equipment for predicting SB, indicating the importance of simulations for each fee and time financial savings in production.

Different studies recommend exceptional numerical methods (e.g., FEM, SVR, ANN), with various levels of accuracy and computational complexity.

What are the most cost-effective and scalable numerical processes for commercial settings? Can hybrid models combining FEM and device getting-to-know yield advanced predictive accuracy?

1.3.4 Experimental investigations and validation

Zhang et al. [11] targeted die from layout for SB management and found that iterative layout methods can yield correct products without needing to recognize fabric residences.

Esmailizadeh et al. [12] compared experimental results with simulations, highlighting the accuracy of anisotropic yield standards in SB prediction.

There's a consensus that experimental validation is important for confirming simulation consequences, and mixing both methods affords first-class outcomes for procedure optimization.

Some research relies greater closely on simulation, while others emphasize the need for real-world experimentation. The stability among the 2 remains a factor of discussion.

How can we streamline the transition from experimental findings to simulation fashions? Could actual-time adaptive simulations based on stay experimental data enhance production?

1.3.5 Advancements in material forming processes

Oliveira et al. [13] mentioned the challenges of forming high-power steels and aluminum alloys, noting how SB and twisting may be managed.

Soualem [14] furnished an in-depth know-how of SB in diverse SMF tactics, emphasizing its importance due to the usage of excessive-stress steels and aluminum alloys.

High-energy steels and aluminum alloys are tough to shape due to SB, but advancements in both materials and method manipulation are gradually mitigating these problems.

There's no clear agreement on the exceptional techniques to cope with those challenges, with some studies that specialize in temperature manipulation and others on system adjustments like various force trajectories.

Are there material innovations (e.g., new alloys, composite substances) that would conquer the demanding situations posed by way of SB extra correctly? How can technique innovations be applied universally throughout diverse materials?

1.3.6 Future directions and open questions

The overarching insights from the studies advocate several habitual themes and challenges, together with the importance of temperature manipulation, procedure optimization, and cloth homes in managing SB.

Agreements center on the effectiveness of procedure management and material optimization, whereas disagreements arise regarding the preferred numerical techniques and forming methods.

Open questions include:

1. How can simulation accuracy be in addition stepped forward to decrease reliance on steeply-priced experimental validation?

2. Can novel substances or composites offer a substantial benefit in controlling SB in stretch forming?

3. What are the most scalable and cost-powerful optimization strategies for industrial applications, thinking about cloth, technique, and system constraints?

2. EXPERIMENTAL PROCEDURE

2.1 Material preparation and experimental procedure

Aluminum alloy Al 6061 sheet for the test sample has a thickness of 1.62 mm. The reason of choosing this type of material is due to its wide applications in the production process of the skin components of airplanes [15] and many other applications. The chemical analysis of this alloy was conducted via the National Center of Quality Control, as revealed (NCQC) in Table 1, together with the standard alloy for comparison purposes.

In the present research, a whole test rig was produced and evolved, and the V-die method using a die having a V-shape was utilized, as depicted in Figure 4. In such a method, each of the two blank ends is firmly kept in tension via an adaptable gripper that moves to stretch the blank over the V-die. The last work-part form is shaped via the influence of the V-die as the sheet metal is hydraulically shifted toward this block.

Table 1. The chemical composition of the used and standard aluminum Al 6061 alloy

Elements (%)	Used	Standard
Cr	0.185	0.04 - 0 .35
Cu	0.224	0.15 - 0.40
Fe	0.37	Max. 0.7
Mg	0.81	0.80 - 1.20
Mn	0.10	Max 0.15
Si	0.435	0.40 - 0.80
Ti	0.15	Max. 0.15
Zn	0.026	Max. 0.25
Al	97.7	95 - 98.6

Figure 4. The test rig showing the use V-die shape (90°) in the stretch forming process

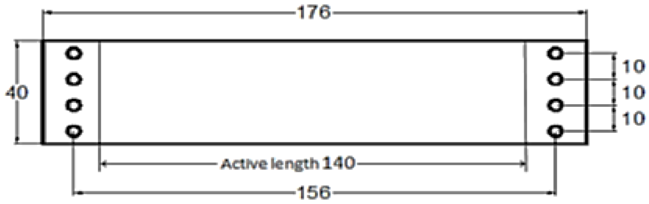


Figure 5. The used test specimen

The test specimen was prepared from the Al 6061alloy sheet using a specially designed and manufactured steel template to obtain the required specimen size with a sheet thickness of 1.6 mm, as displayed in Figure 5, and a CNC cutting machine was used to finish the whole surfaces of specimen edges.

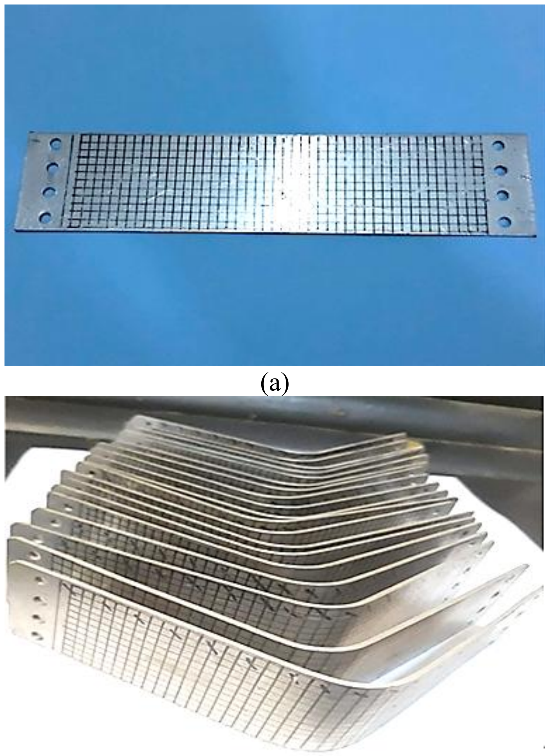
Two types of stretch-forming process, including pre-stretch forming and post-stretch forming were conducted using two levels of stretching forces and stretching speeds as input factors to obtain their effect on the induced sprig-back of the stretched formed specimens, as shown in Table 2. DoE with the RSM was used to establish the design matrix for the input factors (stretching speed and force) and the outputs (SB) for each type of the stretch forming process, comprising 13 runs (tests), as depicted in Tables 2 and 3. Figure 6 elucidates the form of the tested specimens at different stretching forces and speeds. At the end of each test for both pre-stretch and post-stretch forming processes, the SB of the sheet metal specimen was measured using a protractor (±2′) for measuring the SB of the all stretched formed specimens in terms of Δ angle (%). All the results of the measured SB of all stretched specimens are also given in Tables 3 and 4.

Table 2. Used levels of stretching speed and stretching force

Input Factor	Unit	Used Levels	
		-1	+1
Stretching speed	m/min	0.30	0.60
Stretching force	N	4000	6000

Table 3. Matrix design of the actual input factors and the outputs in the pre-stretch forming process

Run No.	Stretching Speed (m/min)	Stretching Force (N)	SB in Pre-Stretching Δ Angle (%)
1	0.30	4000	1.13
2	0.60	4000	1.27
3	0.30	6000	1.90
4	0.60	6000	0.30
5	0.15	5000	2.00
6	0.75	5000	0.34
7	0.45	3000	1.24
8	0.45	7000	1.10
9	0.45	5000	1.20
10	0.45	5000	1.13
11	0.45	5000	1.15
12	0.45	5000	1.18
13	0.45	5000	1.15



(a)

(b)

Figure 6. (a) Specimen before forming and (b) Specimens after forming

Table 4. Matrix design of the actual input factors and the outputs in the post-stretch forming process

Run No.	Stretching Speed (m/min)	Stretching Force (N)	SB in Pre-Stretching Δ Angle (%)
1	0.30	4000	0.75
2	0.60	4000	0.54
3	0.30	6000	0.38
4	0.60	6000	0.14
5	0.15	5000	0.72
6	0.75	5000	0.13
7	0.45	3000	0.90
8	0.45	7000	0.16
9	0.45	5000	0.46
10	0.45	5000	0.41
11	0.45	5000	0.45
12	0.45	5000	0.42
13	0.45	5000	0.43

3. RESULTS AND DISCUSSION

3.1 Modeling of SB in pre-stretch forming process

The average responses determined for the SB of pre-stretch forming process, listed in Table 3, were utilized in computing the models of the response surface per response employing the least-squares technique.

For the prediction of SB prediction, a reduced quadratic model in the coded terms was analyzed with the backwards elimination of insignificant coefficients. Table 5 reveals the statistical ANOVA analysis conducted via the software for the remaining terms. And, the model is significant at a confidence of 95%. It's noticed that the stretching speed (A), the stretching force and their interaction (AB) are significant terms. Also, the lack of fit test exhibits a good model. Such model demonstrates that merely the Table 3 terms (A, B, and AB) possess the uppermost influence upon the SB, however the term (B) has a slight influence on SB. The backward elimination technique examined a simplified quadratic model in coded variables for predicting SB followed by unimportant coefficient elimination. Design Expert software conducted statistical ANOVA analysis to validate the model significance with 95% confidence level (Table 6). The critical model factors include stretching speed (A), stretching force (B) and their interaction (AB) while the lack of fit test shows acceptable model accuracy.

The eventual equation of SB in terms of the actual factors is:

$$\text{Spring back (pre-stretching)} = -3.969233 + 111.84444 \times \text{Stretching speed} + 1.26500E\text{-}0003 \times \text{Stretching force} - 2.90000E\text{-}003 \times \text{Stretching speed} \times \text{Stretching force} \quad (1)$$

The statistical parameters for the model are shown in Table 7.

Table 5. ANOVA for response surface quadratic model for SB in pre-stretch forming process

Source	Sum of Squares	df
Model	2.68	3
A-Stretching Speed	1.90	1
B-Stretching Force	0.019	1
AB	0.76	1
Residual	0.011	9
Lack of Fit	8.079E-003	5
Pure Error	3.080E-003	4
Cor Total	2.69	12

Table 6. ANOVA findings for quadratic response surface model pertaining to SB in pre-stretch forming process

Mean Square	F-value	p-value Prob F
0.89	720.53	< 0.0001 significant
1.90	1535.65	< 0.0001
0.019	15.49	0.0034
0.76	610.46	< 0.0001
1.240E-003		
1.616E-003	2.10	0.2463 not significant
7.700E-004		

Table 7. Statistical parameters and model adequacy metrics for SB in pre-stretch forming procedure

Std. Dev.	0.035	R-Squared	0.9959
Mean	1.16	Adj. R-Squared	0.9945
C.V. (%)	3.03	Pred. Squared	0.9880
PRESS	0.032	Adeq. Precision	85.500

Via noting the normal probability plot shown in Figure 7 for the SB data, the residuals, in general, locate upon a straight line, indicating that the errors being normally distributed. And, in accordance with the Figure 8 depicting the residuals against the predicted responses for the data of SB, it's noticed that there're no clear patterns or an unusual structure, indicating that the models being adequate.

Figure 9 manifests the predicted versus actual data for the SB data in pre-stretching for comparison, and Figure 10 reveals the SB perturbation which depicts the influence of the stretching speed, as well as the stretching force upon the SB in the utilized levels, range; the stretching speed possesses a higher influence upon the SB than the stretching force at the higher input factors levels; however, the stretching force has no influential effect on the SB at the lower and higher levels. Figure 11 evinces that the interaction (combined effect) of the two input factors occurs beyond the design center 0.45 m/min in stretching speed and 5000 N in stretching force for 1.16% for SB.

The two-dimensional contour plot of SB in terms of stretching speed and stretching force in Figure 12. According to the figure, one can notice that the rise in the stretching speed and stretching force individually causes a decrease in the SB. And, the increase in stretching speed at a lower stretching force 4000 N resulted in more SB due to the effect of the strain rate caused by the increase of speed during the pre-stretching process, while the increase in the stretching force at a lower stretching speed also resulted in more SB. This is attributed to the formation of higher developed strains in the deformed material caused by higher applied force in the pre-stretching process. This means increasing both stretching force and speed individually increases the SB. In other words, SB will reduce if both speed and force are increased together, as manifested in Figure 12 due to their combined effect. About the interaction of stretching speed and force interaction, also such figure evinces that at nearly 0.45 m/min in stretching speed and 5000 N in stretching force for 1.16% for SB. The joined effect of such input factors provides elevated SB similar to that resulted in via every one separately.

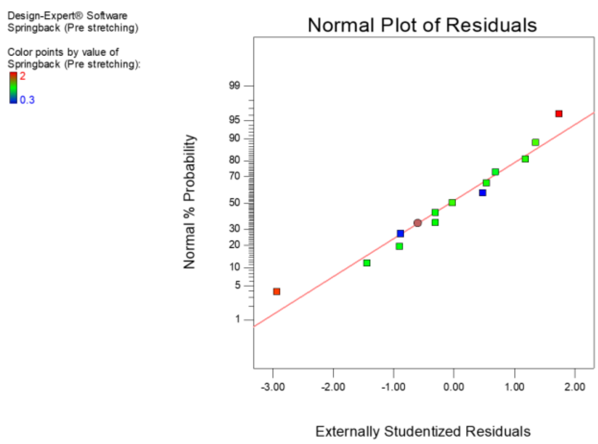


Figure 7. The normal distribution of sprig-back data in pre-stretching

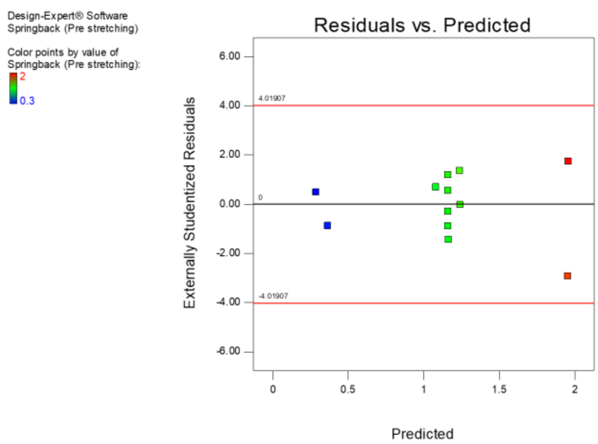


Figure 8. Residual versus predicted data for SB data in pre-stretching

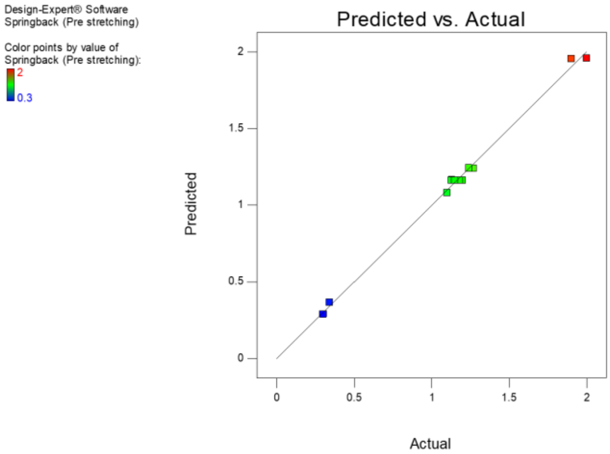


Figure 9. Predicted versus actual data for SB data in pre-stretching

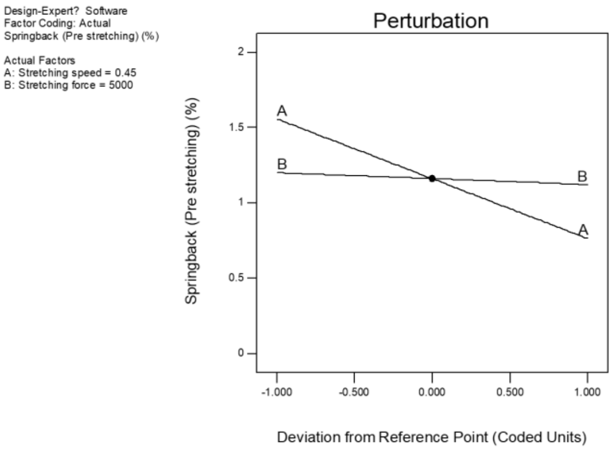


Figure 10. The perturbation of SB data in pre-stretching

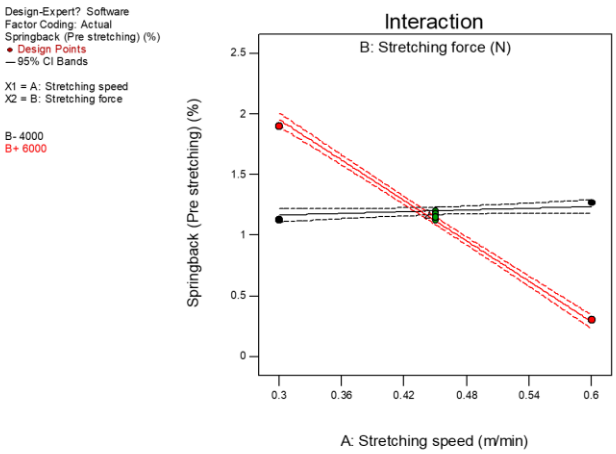


Figure 11. Interaction of the stretching speed and stretching force

The three-dimensional surface plot of SB in terms of stretching speed and stretching force is viewed in Figure 13 and verifies the remarks stated overhead in the two-dimensional plot. And, it can be noted that the rise in the stretching speed and stretching force resulted in a rise in the value of SB at their elevated level, whereas the gas pressure rise is slightly elevated, whereas at nearly close to their center level (design center point), their joined influence provided the lowermost SB value.

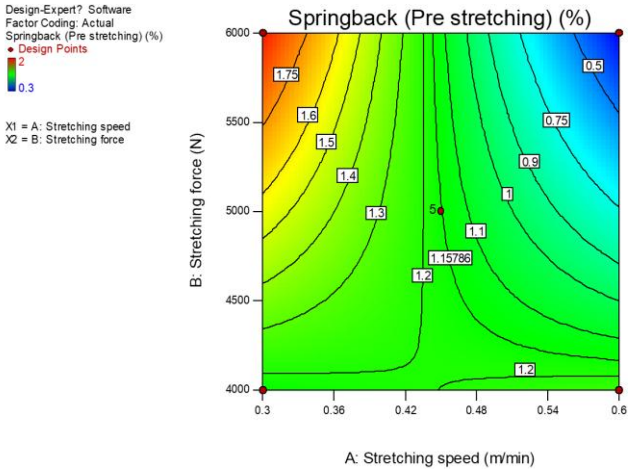


Figure 12. 2D contour graph of SB in terms of stretching speed and stretching force in pre-stretching

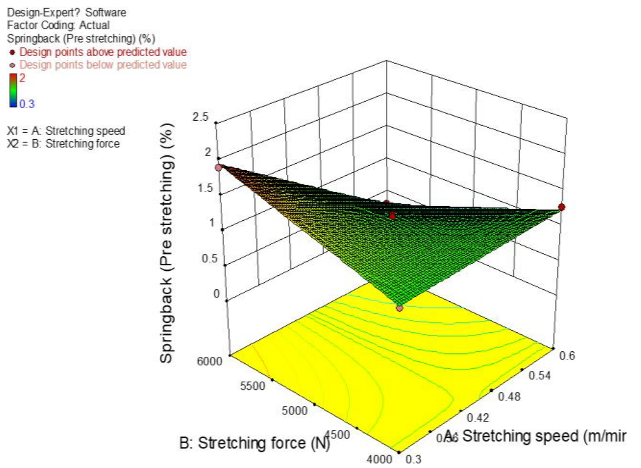


Figure 13. 3D surface plot of SB in terms of stretching speed and stretching force in pre-stretching

3.2 Modeling of SB in post-stretch forming process

Likewise, for the SB outcomes listed in Table 4 for the post-stretch forming process, a reduced quadratic model in coded terms was obtained via the backward elimination of insignificant coefficients. The ANOVA results are revealed in Table 8. Such a model has a significant level of confidence 95%. Also, in this model, the stretching speed (A), stretching force (B), and its squared terms (B^2) are significant. Such a model exhibits that such Table 3 terms have the uppermost influence upon SB. Additionally, there's no interaction between stretching speed and stretching force. Furthermore, the lack of fit test demonstrates a virtuous model.

Analyzers used backward elimination to take away insignificant coefficients from a reduced quadratic model expressed in coded terms. Table 9 demonstrates the results obtained from ANOVA testing for the spring back (SB) performance in post-stretch forming when using quadratic response surface modeling. The stretching speed (A) along with stretching force (B) and both variables squared (B^2) function as this model's significant elements. The research found that stretching speed along with stretching force had no significant interaction. The model exhibits good data fit according to the results of the lack of fit test.

Table 8. ANOVA results for response surface reduced quadratic model for SB in post-stretching

Source	Sum of Squares	df
Model	0.66	3
A-Stretching Speed	0.22	1
B-Stretching Force	0.42	1
B^2	0.015	1
Residual	5.513E-003	9
Lack of Fit	3.793E-003	5
Pure Error	1.720E-003	4
Cor Total	0.66	12

Table 9. ANOVA results for quadratic response surface model for SB in post-stretch forming process

Mean Square	F-value	p-value Prob F
0.22	358.28	< 0.0001 significant
0.22	361.47	< 0.0001
0.42	688.76	< 0.0001
0.015	24.62	0.0008
6.125E-004		
7.585E-004	1.76	0.3012 not significant
4.300E-004		

Table 10. Statistical parameters and model adequacy measures for SB in post-stretch forming process

Std. Dev.	0.025	R-Squared	0.9971
Mean	0.45	Adj.R-Squared	0.9889
C.V. %	5.46	Pred. Squared	0.9825
PRESS	0.012	Adeq.Precision	56.244

Statistical parameters and model adequacy metrics for post-stretch forming process evaluation demonstrate the model's robustness through high R-squared values and good precision in Table 10.

The eventual SB equation in terms of the actual factors is:

$$\text{Spring back (pre-stretching)} = 2.39034 - 0.90556 \times \text{Stretching speed} - 4.33488\text{E-}004 \times \text{Stretching force} + 2.45988\text{E-}008 \times \text{Stretching force}^2 \quad (2)$$

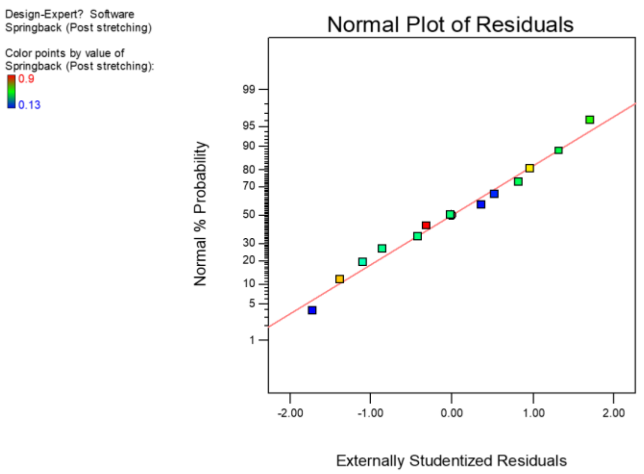


Figure 14. Normal distribution of SB in post-stretching

To statistically check such model adequacy, a normal probability plot of residuals for the data of SB evinced that these residuals (errors) generally fall upon a straight as well as they're normally distributed, as shown in Figure 14. And, there are no obvious patterns or unusual structures, indicating that the models are adequate, see Figure 15. Also, Figure 16 displays the predicted versus actual SB data for the comparison reason. In addition, Figure 17 manifests the perturbation of SB which portrays the influence of stretching speed and force upon the SB over the utilized levels range; the stretching force has a slight impact upon the SB than stretching speed at the lower input levels, whereas the latter possesses a slight influence upon the SB at the higher input levels.

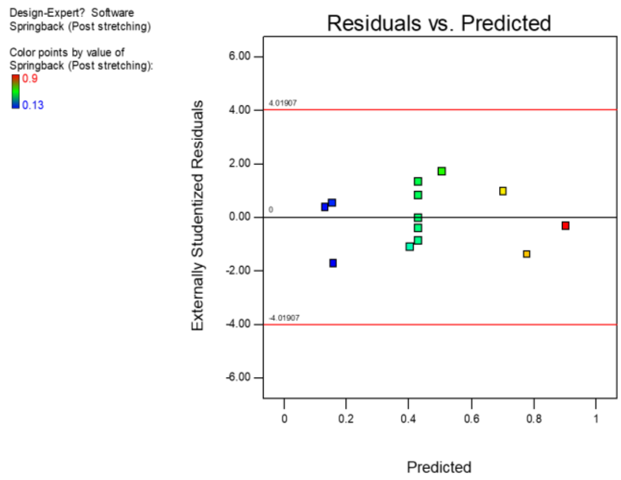


Figure 15. Residual versus predicted data for SB data in post-stretching

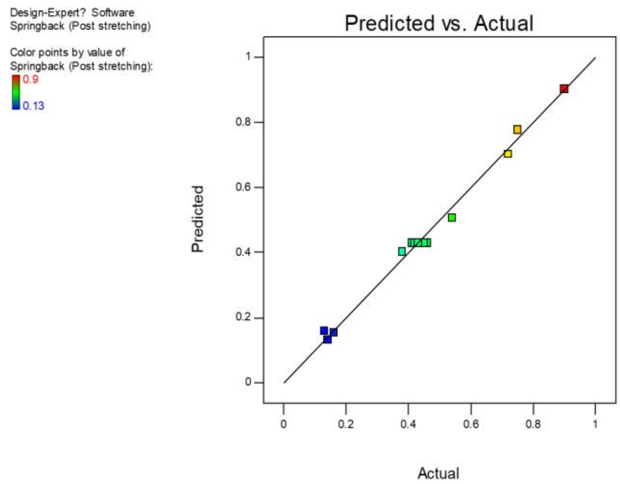


Figure 16. Predicted versus actual data for SB data in post-stretching

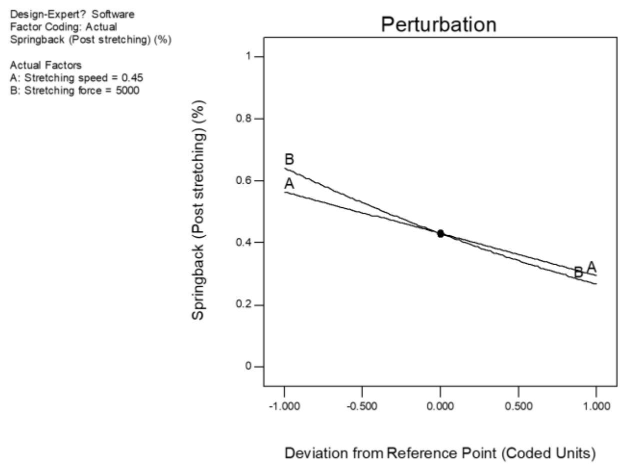


Figure 17. Perturbation of SB data in post-stretching

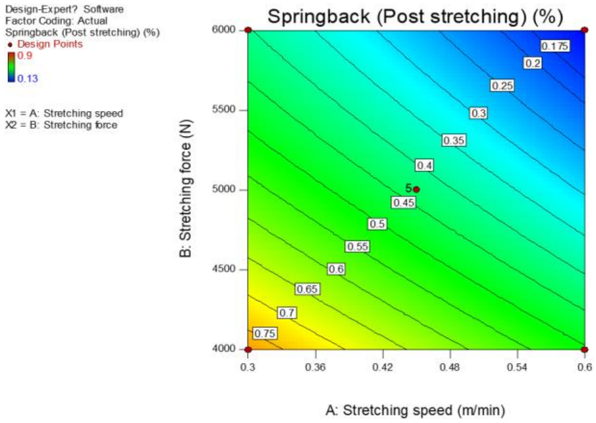


Figure 18. Two-dimensional contour plot of SB in terms of the input factors in post-stretching forming process

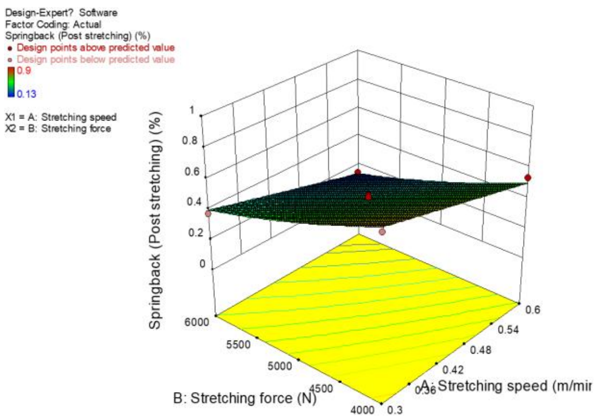


Figure 19. Three-dimensional surface plot of SB in terms of the input factors in post-stretching forming process

Referring to Figure 18 for the two-dimensional contour plot, one can notice that the SB generally reduces with the rise of both stretching force and stretching force individually at their higher levels. And, the SB possesses generally the highest value more than 0.75% at the lower levels of both stretching speed and stretching force, while at the higher input levels, the SB has generally the lowest value less than 0.175%. And, this is attributed to the combined influence of stretching speed as well as stretching speed owing to the less deformation influence caused via the strain hardening.

The three-dimensional surface plot of SB in terms of the input factors in post-stretching forming process is elucidated in Figure 19. This figure verifies the same observation exhibited in Figure 18; this means that the SB has the highest value at the lower levels of stretching force and stretching speed 4000 N, 0.3% due to their combined effect, whereas SB possesses the lowest value at the highest levels of these input factors 6000 N, 0.6% due the abovementioned reason. Also, such a figure confirms that individually the increase of either stretching force or stretching speed reduces the SB at their higher levels.

3.3 Determination of the optimum conditions and SB values in pre- and post- stretching process

The numerical optimization was conducted via the DoE software for obtaining the optimal amalgamations of the input factors for fulfilling the favorable needs, relying upon the outcomes from the predicted quadratic models for the SB as responses in terms of stretching speed and stretching force. For modifying such predicted models, a new objective function named ‘Desirability’ was assessed as well as to be maximized by numerical optimization; the ranges from zero to one at the goal. And, the ultimate aim of the optimization in the present work was to obtain the minimum response that concurrently satisfied all variable characteristics. Constraints of every variable for the SB numerical optimization were used, and the input factors were chosen for their utilized levels, whereas the responses were selected to be the minimum. Therefore, a single likely solution satisfied such constraints to obtain the minimum predicted values of SB (0.287% in pre-stretching and 0.132% in post-stretching), as depicted in Table 7 with a maximum desirability value of 0.999 at the optimum values of stretching speed 0.60 m/min and stretching force 6000 N.

3.4 Validation of the optimum SB in the pre-and post-stretching process

In this step, confirmation tests were carried out at the optimal SB to confirm the authentication of the minimum SB values listed in Table 11. And, the outcomes of such tests are listed in Table 12 for the reason of comparison between the predicted and experimental outcomes.

Also, following the shown outcomes in such table, the maximum error between the experimental and predicted error for SB is 4.33% in the pre-stretching forming process and 5.71% in the post-stretching forming process. Figures 20 and 21 reveal the predicted values of SB in the pre-stretching and post-stretching forming processes.

Table 11. Predicted SB values at the optimum conditions of pre-stretching and post-stretching processes

Parameter	Value
Stretching speed (m/min)	0.60
Stretching force (N)	6000
SB in pre-stretching (%)	0.287
SB in post-stretching (%)	0.132
Desirability	0.999

Table 12. Confirmation test results at the optimal conditions

Parameter	Value
Stretching speed (m/min)	0.60
Stretching force (N)	6000
Exp. SB in pre-stretching (%)	0.30
Pred. SB in pre-stretching (%)	0.287
Exp. SB in post-stretching (%)	0.140
Pred. SB in post-stretching (%)	0.132

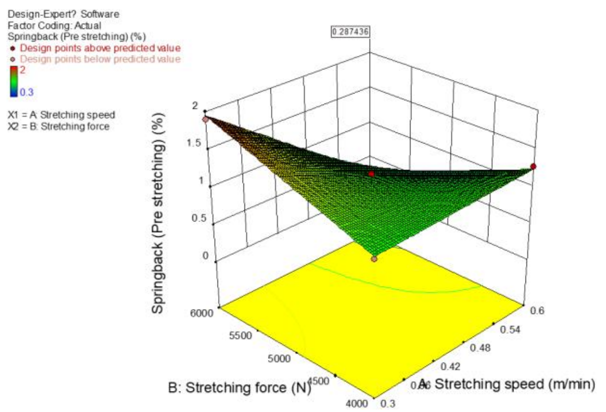


Figure 20. The predicted value of SB in the pre-stretching process

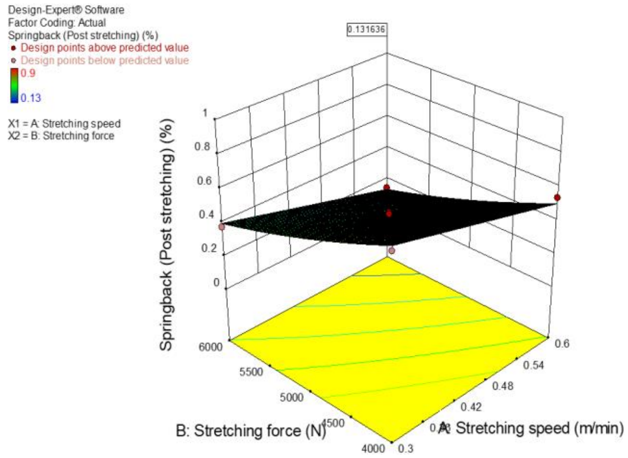


Figure 21. The predicted value of SB in post-stretching process

4. RATIONALE FOR DOE WITH RSM AND ANOVA

DoE allows for a systematic exploration of a couple of factors, which include stretching pace and stretching force simultaneously, minimizing the number of experiments required. RSM is used to model the connection between those factors and the response in this situation, SB, allowing the identification of the most efficient operating situations. ANOVA technique assesses the statistical significance of each aspect and their interactions, making sure that the model is strong and reliable. Compared to FEM, which requires large computational sources and time to version and simulate the stretch-forming process, DoE with RSM gives an empirical approach to optimization this is faster and less resource-extensive. Additionally, preheating techniques to limit SB are high-priced because of electricity costs and the need for material safety towards oxidation. DoE-primarily based strategies do now not require additional heating techniques, making them extra price-green. Unlike FEM, that's primarily based on simulation and frequently requires validation through experiments, the DoE technique is grounded in experimental facts from the outset. By leveraging actual test effects, the model generated through RSM displays the real-global conduct of the cloth and method, providing extra immediate and actionable insights. For example, in the case of aluminum alloy Al 6061, experiments have been carried out at diverse stages of stretching speed and force, and the DoE framework provided a statistical version for predicting SB with excessive accuracy.

DoE coupled with RSM offers now not only the most suitable manner parameters but additionally insights into the interplay effects between the one's parameters. For example, the interaction between stretching pace and stretching force was studied in both pre- and publish-stretching procedures, and it changed into discovered that the blended results of each factor considerably influenced SB. This nuanced know-how is often tougher to extract from conventional FEM models, where interplay consequences may not be explicitly modeled. DoE with RSM is scalable throughout one-of-a-kind forms of materials and forming conditions. It can be tailored for various alloys and procedures, providing flexibility this is more difficult to acquire with FEM simulations, which ought to be tailored to particular cloth houses and geometries.

5. COMPARING PRE AND POST-STRETCHING CONDITIONS AT OPTIMIZED SETTINGS FOR COLD STRETCH

Pre-stretching: This technique tends to reduce the occurrence of spring-returned by allowing some preliminary cloth deformation earlier than the very last form is completed. The cloth is stretched before it undergoes the final forming operation, which could result in reduced residual stresses, and for that reason, much less spring-lower back. Pre-stretching results in smoother material flow and less unexpected elastic recuperation.

Post-stretching: In evaluation, post-stretching introduces the stretching process after the number one forming has been conducted. This approach can be extra vulnerable to SB because the cloth, which has already been bent or fashioned, is subjected to additional stresses that could grow the elastic recovery effect. From a quantitative attitude, research like the ones mentioned by way of Burchitz [16] and Zhang et al. [17] imply that better-stretching strains result in notably decreased spring-again, in particular when substances inclusive of Al 6061 are used. For example, increasing the stretching stress through a factor of 10% can result in as lots as a 20-30% reduction in spring-lower back, depending on the precise alloy and method.

To verify the most fulfilling situations for minimizing spring-lower back, confirmation runs may be carried out by making use of the optimized parameters derived from experimental and theoretical models. For instance, Taotao Fang et al. [18] carried out successful reductions in spring-returned and sheet thinning by optimizing punch force and stretching quantity through the usage of numerical simulations, observed by using experimental validation. Similar runs for Al 6061 could involve checking out one-of-a-kind combos of stretching pressure and pace to make sure that the process minimizes spring-lower back without causing immoderate thinning or defects. Reduced SB results in fewer publish-forming corrections, enhancing performance within the production cycle [19]. The lower the spring-lower back, the less guide adjustment and rework wanted, translating into value savings. By decreasing spring-returned via pre-stretching and optimized pressure settings, manufacturers can attain higher dimensional accuracy in components, which is vital for industries like aerospace wherein tight tolerances are crucial. Optimized settings reduce the need for thicker materials to atone for SB, therefore enhancing cloth efficiency [20].

In summary, the assessment of pre- and put-up-stretching beneath optimized situations reveals that pre-stretching usually affects much less spring-lower back, which may be proven via affirmation runs with the ideal settings. The sensible implications of minimizing spring back consist of advanced accuracy, performance, and fabric utilization in production strategies [21, 22].

6. COMPARISON RESULTS WITH PREVIOUS STUDIES

Reduction of SB with Increased Stretching Strain: The current look aligns with previous studies, which include the work with the aid of Burchitz [16] and Liu et al. [23], which established that growing the stretching stress ends in a reduction in SB. Both studies show that pre-stretching before forming can decrease the residual stresses within the fabric, decreasing elastic recuperation put up-forming. This consistency validates the general principle that higher strains lessen SB, especially in aluminum alloys like Al 6061.

- Material behavior in cold stretch forming: The observed fashion that SB decreases with thicker materials and better stretching forces is consistent with research consisting of He et al. [3] and Uemoria et al. [24]. These works affirm that cold stretch forming of alloys, especially underneath optimized force and pace conditions, leads to predictable spring-returned behavior and dimensional accuracy upgrades.
- Confirmation of numerical and experimental data: The consistency among numerical simulations and experimental facts found within the present day take a look at is likewise echoed in previous works, which include the ones by Fang et al. [18] and Ao et al. [25]. Both types of research confirmed that finite element analysis (FEA) and RSM will be efficiently used to predict and limit SB in aluminum alloys, confirming the reliability of simulation fashions.
- Magnitude of SB reduction: While the cutting-edge observation suggests vast SB reduction through pre-stretching, the volume of this discount seems to be slightly smaller than in a few preceding research, along with Arunkumar et al. [6] and Zhang et al. [17], where large reductions have been found under exclusive forming conditions. These variations can be attributed to versions in material homes, manner parameters, or the particular alloy composition utilized in those studies.
- Post-stretching SB behavior: Some studies, such as those by Sasaki et al. [9], indicated that post-stretching could still result in relatively low SB under controlled conditions. However, the current study suggests that post-stretching introduces more significant SB than pre-stretching. This discrepancy might arise from differences in how the stretching forces were applied or differences in tool geometry and process sequence.

7. CONCLUSIONS

1. The increase in both stretching force and stretching speed forming processes reduces the SB of the aluminum alloy (Al 6061).

2. The increase in both stretching force and stretching speed forming processes individually reduces the SB of the aluminum alloy Al 6061.

3. The interaction (combined effect) of the stretching speed and stretching force takes place beyond the center of the input level at nearly 0.45 m/min stretching speed and 5000 N force for 1.16% SB).

4. In pre-stretching process, the stretching speed possesses a higher influence upon the SB than the stretching force at the lower input factors levels; however, the stretching force has no influential effect on the SB at the lower and higher levels. Whereas, in post-stretching process, the stretching force has a slight impact upon the SB than stretching speed at the lower input levels, whereas the latter possesses a slight influence upon the SB at the higher input levels.

5. Referring to the numerical optimization, the minimum predicted values of SB are 0.287% in pre-stretching and 0.132% in post-stretching process with a maximum desirability value of 0.999 at the optimal values of stretching speed 0.6 m/min and stretching force 6000 N. Both experimental and predicted SB values in post-stretching forming process are less than those in the pre-stretching forming process; this means that the post-stretching forming can be recommended for forming the sheet of the Aluminum alloy (Al 6061).

6. Confirmation tests portrayed that the maximum errors between the experimental and predicted results is 4.33% in pre-stretching forming process and 5.71% in post-stretching forming process, respectively.

7. The use of DoE with RSM and ANOVA gives numerous advantages over FEM and preheating in controlling SB in SMF. It allows for the optimization of method parameters, reduces prices related to simulation and electricity intake, and gives statistically established fashions based totally on real-international experiments. This technique is specifically beneficial for decreasing SB without the need for preheating, imparting an efficient and adaptable answer for enhancing the accuracy and performance of sheet-metallic forming processes.

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