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SPRINGBACK PHENOMENON ANALYSIS IN SHEET METAL FORMING OF ALUMINUM 2024 USING RUBBER PRESS MACHINE IN THE AIRCRAFT INDUSTRY

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Abstract: Springback, a critical issue in sheet metal forming, challenges precision in aerospace component manufacturing, particularly in the aircraft component manufacturing industry. This study investigates springback in the Rubber Press process using Aluminum 2024-T3 and 2024-T0 materials, with varying thicknesses (0.6–1.2 mm) and forming pressures (200–600 bar). A predictive model is developed by combining Taguchi's experimental design with Finite Element Analysis (FEA) validation using AutoForm software. Key influencing factors, including material properties, thickness, and forming pressure, are analyzed to evaluate their effects on springback. Results show that higher pressure and increased thickness minimize springback, enhancing forming accuracy. The integration of regression and ANOVA provides statistical insights into optimizing forming parameters. The study contributes to improving production efficiency and quality, offering tailored strategies to address springback issues in aerospace manufacturing. Future work may explore the role of elastomer pad deformation in the Rubber Press process to optimize it further.
Keywords: springback, sheetmetal forming, hydroforming, aluminum 2024, Taguchi method.

1. INTRODUCTION

Springback, the elastic recovery of sheet metal after forming, poses a significant challenge in the aerospace industry. At the industry level, this issue leads to deviations in formed parts, necessitating additional processes to meet design specifications. The Rubber Press machine, which operates at a reduced pressure of 600 bars compared to the expected 1000 bars, exacerbates the problem. Over the past five years, deviations between actual and standard times have increased, highlighting inefficiencies in the manufacturing process. Chen investigated wrinkling and springback in aluminum alloys (2024-O, 7075-O, 2024-T3) under 300-bar pressure, finding that larger flanges and smaller radii exacerbate wrinkles [1]. Hatipoglu focused on springback in straight flanging of aluminum 2024-T3 using hydroforming, identifying significant influences of forming pressure, material thickness, and bending radius [2]. Subsequent studies expanded on these findings, applying Taguchi methods [3], Fan Investigated the springback of 2219-W aluminum alloy sheets through V-shaped bending using an experimental approach and numerical simulations [4], and material-specific analyses such as aluminum-magnesium alloys [5] and Liu researching the springback of high strength hollow aluminum profiles using an experimental approach, Finite Element Simulation [6].

In the study by Li, springback was investigated using microscopic analysis and predictive modeling for aluminum AA6061 and Al–Mg–Si–Cu materials [7]. Wang studied springback using an experimental approach and finite element simulation on AISI 316L material during roll forming [8]. Zhang examined springback through an experimental approach on aluminum 2050 material using roll bending machines [9]. He predicted springback using an experimental approach on superalloy foil material with fatigue tests [10].

Fan investigated springback predictions through an experimental approach on aluminum 2024-W material using a rubber press machine at 300-bar pressure. Corona explored springback predictions through an experimental approach and FEA for aluminum tube-T6 material using a stretch forming machine [12]. Ahn studied springback predictions through an experimental approach and FEA on Inconel 690 helical tube material using a bending tube machine [13].

Aerens investigated springback predictions through an experimental approach and FEA on AISI 304 material using bending forming machines [14]. Maqbool studied springback predictions through an experimental approach on AISI 304 material using hemispherical forming [15]. Zhang examined springback predictions through an experimental approach on carbon steel material using bending forming [16]. Zhang investigated springback predictions through an experimental approach on hollow aluminum alloy profiles using stretch forming [17]. Saito studied springback predictions through an experimental approach on high-strength steel material using bending forming [18]. Ma studied springback predictions profile-based shapes [19]. Zhang studied springback control for creep age forming of aluminum alloy [20]. Raval studied Incremental Sheet Forming (ISF) experiments were conducted using a 3-axis CNC milling machine, Design of experiments use Taguchi method with 4 factors and ANOVA for analysis data [21].

Despite these advancements, most studies have not addressed the combined effects of high pressures (up to 600 bar), material temper variations (2024-T3 and 2024-T0), and thickness variations. This study builds upon existing literature by integrating experimental design, FEA, regression analysis, and ANOVA to develop a robust predictive model for springback under these industrial conditions, specifically tailored for an aircraft-components manufacturing industry Rubber Press process.

2. MATERIALS AND METHODOLOGY

This study uses Aluminum 2024-T3 and 2024-T0, thicknesses of 0.6, 0.8, 1.0, and 1.2 mm. These materials were chosen for their relevance to aerospace manufacturing. The experiments were structured using Taguchi's orthogonal array L18 to evaluate the influence of fourth factors: material hardness (2024-T3 70-80 HB, 2024-T0 25-35 HB), thickness (0.6, 0.8, 1.0, 1.2mm), radius (5mm and 2.5mm) and forming pressure (200, 400, 600 bar). To find an Orthogonal array, L18 uses Equations 1, 2, and 3 [22].

Calculating Interaction Degrees of Freedom using Equation 1.

$$\text{Total Dof} = \text{Dof AD} + \text{Dof B} + \text{Dof C} \tag{1}$$

where: Dof AD =2(nAD-1); Dof B = nB -1; Dof C = nC-1

Calculating Interaction Degrees of Freedom using Equation 2.

$$\text{Dof interaksi} = (nA - 1) \cdot (nB - 1) \cdot (nC - 1) \cdot (nD - 1) \tag{2}$$

where: nA=Number of Levels for Factor A; nB=Number of Levels for Factor B; nC=Number of Levels for Factor C; nD=Number of Levels for Factor D.

Calculating the Total Experiments using Equation 3.

$$\text{FLN} = \text{M} + (\text{Total DOF}) + (\text{Dof Interaction}) \tag{3}$$

where: FLN= Total Experiment and M=1.

The selected orthogonal array must have a minimum number of rows that cannot be less than the total number of degrees of freedom [23].

This methodology as shown in Figure 1, ensures efficient analysis of springback factors in Rubber Press processes at an aircraft-components manufacturing industry. This study employs a quantitative method with an experimental and simulation approach. The method involves collecting empirical data through field experiments and validating the data using ANOVA and regression analysis, as well as computer simulations using Finite Element Analysis (FEA). The primary focus of the research is to analyze the effect of process parameters, such as forming pressure and material thickness, on the springback phenomenon in the part-forming process using a Rubber Press machine at an aircraft-components manufacturing industry.

3. RESULTS AND DISCUSSION

The experiments demonstrated that both material thickness and forming pressure significantly influenced the springback phenomenon. Experimental data were validated statistical analysis and using FEA in AutoForm software.

Linear regression analysis using SPSS software is employed to test the accuracy of experimental results obtained through the Orthogonal L18 method compared to the Full Factorial Method. The R-Square value measures how well the model explains the variation in the data, with a value close to 1 indicating an excellent model. If the value is less than 0.05, it suggests that the model is not adequate. The validation results are presented in Table 1.

The interaction between various experimental factors can be quantitatively determined using ANOVA [21]. ANOVA analysis is used to evaluate the significant effects of factors and their interactions on springback based on the experimental results presented in Table 2.

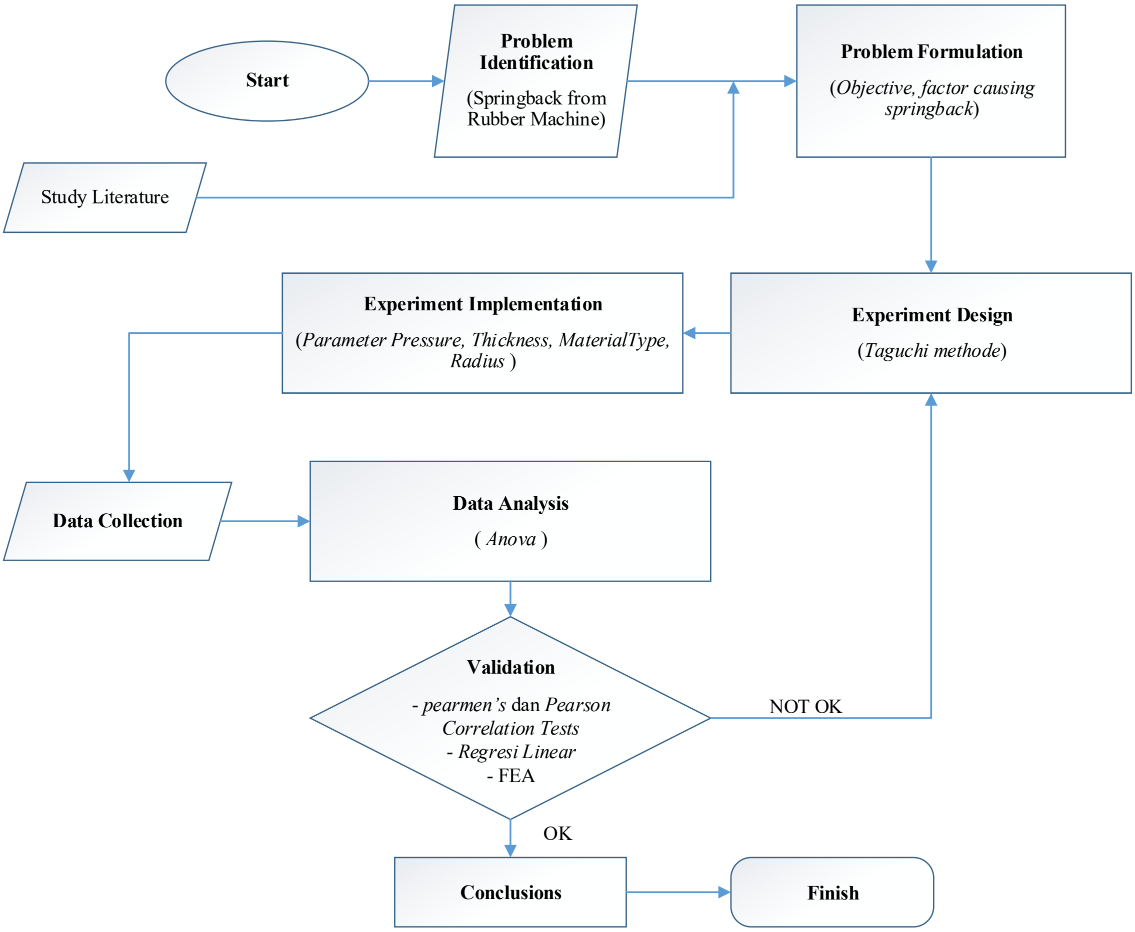

Fig. 1. Methodology Flowchart

The table 1 presents the experimental results of springback measurements on aluminum alloy 2024 in temper conditions T3 and T0 with various thicknesses. The specimens were subjected to different forming pressures and die radii. Both actual springback values and predictions from AutoForm software are listed for comparison.

Table 1. Results of Springback Experiment

Experiment	Material	Pressure [bar]	Radius [mm]	Springback actual [degree]	Springback Autoform [degree]
Specimen 1	2024-T3-0.6 mm	200	5	14.01	16.40
Specimen 2	2024-T3-0.8 mm	400	5	11.22	13.09
Specimen 3	2024-T3-1.0 mm	600	5	9.2	11.03
Specimen 4	2024-T3-1.2 mm	200	5	9.5	9.84

Specimen 5	2024-T3-1.6 mm	400	5	6.02	8.133
Specimen 6	2024-T3-0.6 mm	600	5	12.5	13.5
Specimen 7	2024-T3-0.8 mm	200	5	11.5	13.64
Specimen 8	2024-T3-1.0 mm	400	5	9.12	11.29
Specimen 9	2024-T3-1.2 mm	600	5	8.27	8.75
Specimen 10	2024-T0-0.6 mm	200	2.5	2.5	2.43
Specimen 11	2024-T0-0.8 mm	400	2.5	2.53	1.79
Specimen 12	2024-T0-1.0 mm	600	2.5	0.75	1.79
Specimen 13	2024-T0-1.2 mm	200	2.5	1.5	1.45
Specimen 14	2024-T0-1.6 mm	400	2.5	1.5	1.24
Specimen 15	2024-T0-0.6 mm	600	2.5	1.5	1.88
Specimen 16	2024-T0-0.8 mm	200	2.5	2	1.91
Specimen 17	2024-T0-1.0 mm	400	2.5	1.75	1.85
Specimen 18	2024-T0-1.2 mm	600	2.5	0.5	0.74

Table 2. Validation Results of Springback Experiment

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.423[a]	0.179	0.003	401.779

a. Predictors: (Constant), radius, pressure, material

Table 3. ANOVA Analysis

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	480.710	438.676		1.096	.292
Pressure	-.437	.582	-.183	-.751	.465
Material	-305.657	312.050	-.238	-.980	.344
Radius	74.333	63.133	.285	1.177	.259

The analysis results in Table 3 show that the highest value is for pressure, at 0.465, indicating that pressure has the highest significant effect on springback.

3.1. Pressure To Springback Trend Validation Results

Springback tends to decrease as pressure increases. This trend is consistent in both actual data and AutoForm simulation results, indicating that the AutoForm simulation successfully replicates the effect of pressure on springback. The pressure-to-springback trend is illustrated in Figure 2.

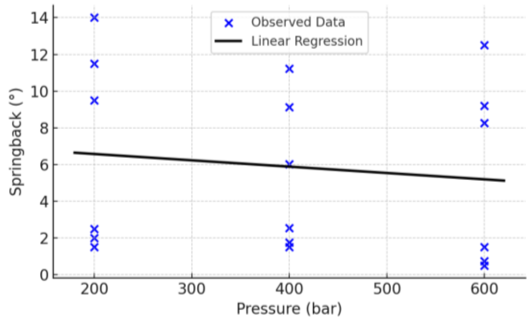

Fig. 2. Relationship Pressure with Springback

The pressure pattern shown in Figure 2 is reinforced by the results of the Spearman's and Pearson correlation analysis conducted using SPSS, as presented in Tables 4 and 5.

Table 4. Correlation Test Data Analysis of Experimental Results Between Pressure and Springback Using the Pearson Method

Correlations		springback	Pressure
Springback [degree]	Pearson Correlation	1	-.031
	Sig. (2-tailed)		.903
	N	18	18
Pressure [bar]	Pearson Correlation	-.031	1
	Sig. (2-tailed)	.903	
	N	18	18

Table 5. Correlation Test Data Analysis of Experimental Results Between Pressure and Springback Using the Spearman's Method

Correlations			springback	Pressure
Spearman's rho	springback	Correlation Coefficient	1.000	-.145
		Sig. (2-tailed)	.	.567
		N	18	18
	Pressure	Correlation Coefficient	-.145	1.000
		Sig. (2-tailed)	.567	.
		N	18	18

The correlation coefficient between machine pressure and springback value in Table 4, is -0.31, and in Table 5, is -0.145. Both values are negative, indicating that as machine pressure increases, the springback value tends to decrease.

3.2. Thickness to Springback Trend Validation Results

Springback decreases as the material thickness increases. This pattern is also observed in the actual data and Autoform results, as shown in Figure 3.
The thickness pattern shown in Figure 3, is reinforced by the results of the Spearman's and Pearson correlation analysis conducted using SPSS, as presented in Table 6 and Table 7.

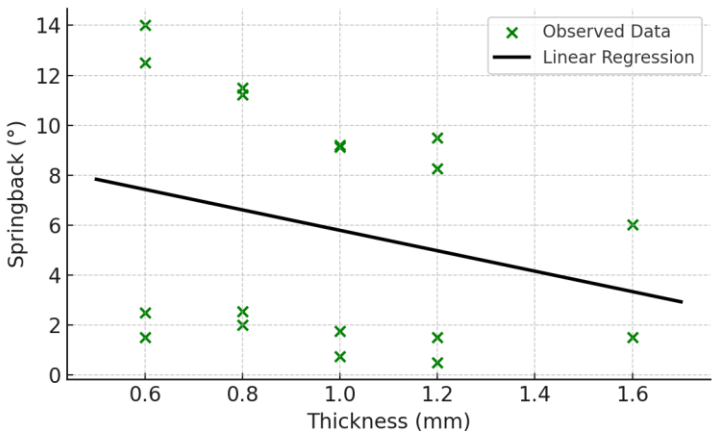

Fig. 3. Relationship Thickness with Springback

Table 6. Correlation Test Data Analysis of Experimental Results Between Thickness and Springback Using the Pearson Method

Correlations		Springback	Thickness
Springback [degree]	Pearson Correlation	1.000	0.878**
	Sig. (2-tailed)	.	<.001
	N	18	18
Material [HB]	Pearson Correlation	.878**	1.000
	Sig. (2-tailed)	<.001	.
	N	18	18

Table 7. Correlation Test Data Analysis of Experimental Results Between Pressure and Springback Using the Spearman's Method

Correlations			springback	material
Spearman's rho	Springback [degree]	Correlation Coefficient	1.000	-.366
		Sig. (2-tailed)	.	.135
		N	18	18
	Material [HB]	Correlation Coefficient	-.366	1.000
		Sig. (2-tailed)	.135	.
		N	18	18

The correlation coefficient between machine material thickness and springback value in Table 6 is -0.274, and in Table 7, it is -0.366. Both values are negative, indicating that as the material thickness increases, the springback value tends to decrease.

3.3. Material Hardness to Springback Trend Validation Results

The material hardness with Temper T3 (harder) shows a higher springback compared to T0 (softer), as shown in Figure 4, the Autoform simulation successfully captures this characteristic. The average difference between the actual and Autoform results for each category is calculated.

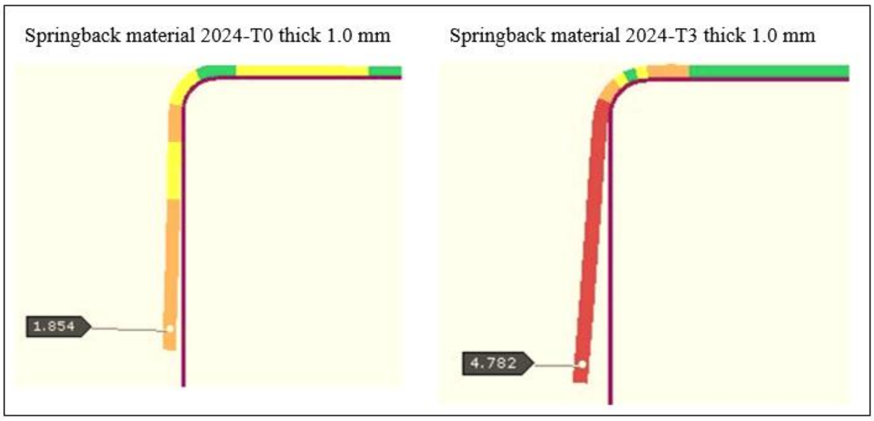

Fig. 4. Relationship Material hardness with Springback

Figure 4, shows the effect of material hardness on springback results from the Autoform software, reinforced by the results of Spearman's and Pearson correlation analysis using SPSS, as presented in Tables 8, and 9.

Table 8. Correlation Test Data Analysis of Experimental Results Between Material Hardness and Springback Using the Pearson Method

Correlations		springback	Thickness
Springback	Pearson Correlation	1.000	.878
	Sig. (2-tailed)	.	<.001
	N	18	18
Material	Pearson Correlation	.878**	1.000
	Sig. (2-tailed)	<.001	.
	N	18	18

Table 9. Correlation Test Data Analysis of Experimental Results Between Material Hardness and Springback Using the Spearman's Method

Correlations			springback	material
Spearman's rho	springback	Correlation Coefficient	1.000	.849**
		Sig. (2-tailed)	.	<.001
		N	18	18
	Material	Correlation Coefficient	.849**	1.000
		Sig. (2-tailed)	<.001	.
		N	18	18

The correlation coefficient between material hardness and springback value in Table 8, is < 0.001, and in Table 9, is < 0.001. Both values are less than 0.05. This indicates that material hardness and springback are correlated. Material with hardness T3 shows a higher springback value compared to hardness of T0.

Based on the data obtained, a predictive model for springback can be developed using linear regression to model the relationship between springback and its independent variables. The results of multiple linear regression analysis are as shown in Table 10.

Table 10. Results Of Multiple Linear Regression Analysis

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.293	0.207	6.25	0	
Radius, [mm]	0.6735	0.0502	13.41	0	1
Thickness, [mm]	-1.1389	0.0901	-12.64	0	1
Pressure [bar]	-0.0016	0.00019	-8.47	0	1

The predictive model for the springback can be formulated as shown in Equation 4.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \quad (4)$$

Prediction Model Distribution for Springback if the following information is given as follows: $X_1 = 5.0$; $X_2 = 1.0$; $X_3 = 400$; $\beta_0 = 10.858$; $\beta_1 = 1.545$; $\beta_2 = -6.188$; $\beta_3 = -0.002951$.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 = 10.858 + (1.545X5) - (6.188X1) - (0.002951X400) = 10.858 + 7.725 - 6.188 - 1.18 = 11.29° \quad (5)$$

Validation the predictive model demonstrated high accuracy with minimal deviation between experimental and simulated results as shown at figure 5.

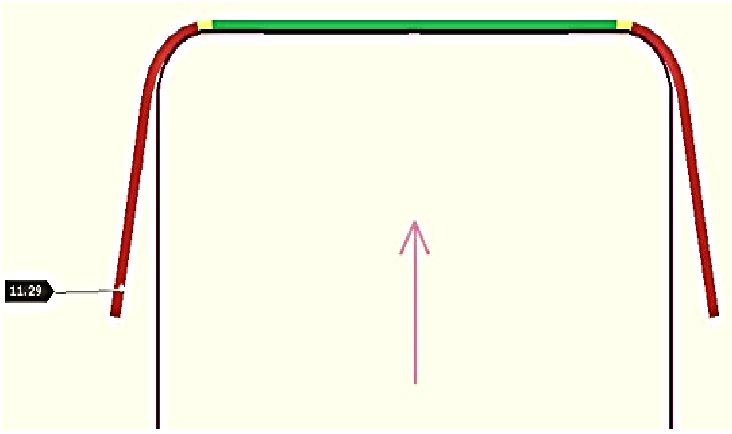

Fig. 5. Validation FEA With Autoform

Based on Equation 4, the springback value is 11.29°. By subtracting 11.29° from the 90° tool angle, the tool angle will be adjusted to 78.71°. The visualization of the results from Equation 4, is shown in Figure 6.

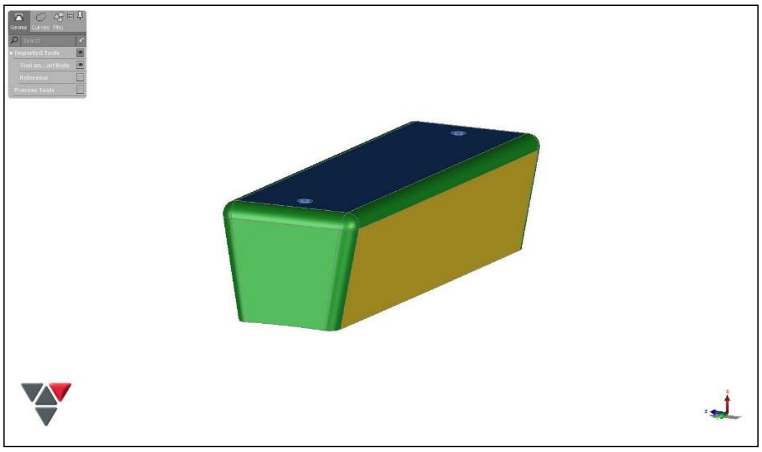

Fig. 6. Tool Angle Adjusted Based on the Results of Equation 4

The simulation was conducted in Autoform on the tool with an adjusted angle, using 2024-T3 material with a thickness of 1.0 mm and a pressure of 400 bar. The simulation results are shown in Figure 7.

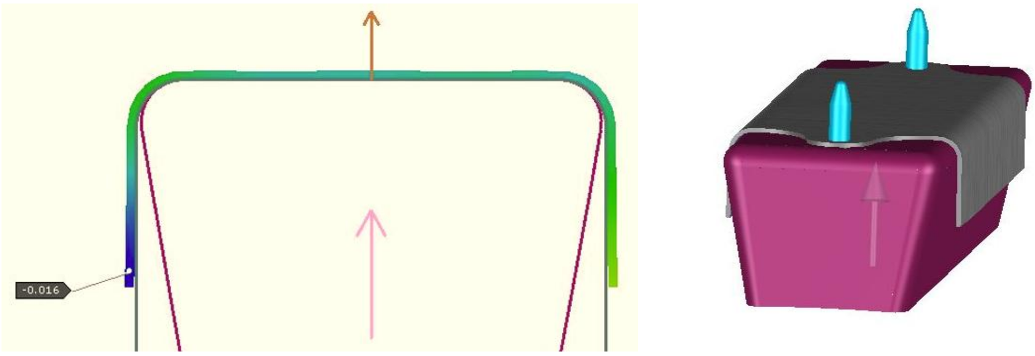

Fig. 7. Simulation Results of Forming Based on Figure 6, Results of Equation 4

The simulation results based on Figure 6, show that the part angle is 89.984°, which is -0.016° from the drawing requirement of 90° show in Figure 7, this value is still within the allowable tolerance of ±0.5°.

4.CONCLUSIONS

The analysis of the correlation coefficients between various factors and springback values reveals important insights into how different parameters affect springback behavior. Firstly, there is a negative correlation between machine pressure and springback values, indicating that as machine pressure increases, the springback tends to decrease. This suggests that higher pressure helps to reduce the springback effect. Similarly, material thickness is also negatively correlated with springback, meaning that as the material thickness increases, the springback value decreases. Thicker materials result in less springback. Furthermore, the correlation between material hardness and springback is significant, with a coefficient less than 0.05, highlighting a correlation between the two. Specifically, materials with Temper T3 (harder) exhibit higher springback values compared to those with Temper T0 (softer). Overall, these results indicate that pressure, thickness, and hardness are key factors influencing springback, with pressure and thickness inversely affecting it, while hardness has a direct relationship with the springback value. The validation results of the springback prediction model, with a value of 11.29°, are confirmed by the Autoform FEA simulation results, which show an angle of 89.984°. This study successfully developed a predictive model for springback in L-bending processes using Rubber Press machines. The findings provide actionable insights for optimizing forming parameters, improving product quality, and reducing processing times at an aircraft-components manufacturing industry. Further research can add the effect of rubber throw pad on springback in the hydroforming process by using a rubber press machine.

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