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Effect of annealing, thickness ratio and bend angle on springback of AA6061-T6 with non-uniform thickness section

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Abstract. Non-uniform thickness section section is considered one of the most effective approaches to reduce automotive part weight. Reduction in term of mass and size result in less fuel consumption and greenhouse gases. Thickness is the most significant parameter to formability, therefore forming a section with non-uniform thickness becomes a great challenge. Improper process and incorrect decision may lead to severe defect and one of the main concerns is the springback. This study will focus on springback behaviour of non-uniform thickness AA6061 strip with complex profile using Taguchi Method. Profile projector (PC 3000) is used to measure the spring back and two-line technique is applied to measure angles (after loading) between two lines. Three parameters (i.e. annealing temperature, thickness ratio and bend angle) are studied, and results determine that the most significant parameter is bend angle, followed by thickness ratio, and then by the annealing temperature of the specimen during bending process.

1 Introduction

The application of lightweight construction is a one of the central challenge in modern transportation engineering. Optimization of lightweight construction can be achieve if material is used only in the areas where stresses appear and if the material used is charged near yield stress [1]. Lightweight components can be classified into two types. Firstly, lightweight construction deals with the application of light materials. The use of light materials keep remain the workpiece geometry but reducing the weight of the whole component. The other one, lightweight construction which deals with different design strategies including the process of forming the component [2]. Formability of the material depends on many factors including thickness, properties of the material and complexity of the formed part. These factors may initiate defect such as springback lead to higher part rejection.

In the manufacturing sector, there are several important things that need to be considered especially safety of passengers in reducing the vehicle weight. Thus, lightweight and crashworthiness are two crucial aspects of the automobile design.

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For example, B-pillar as shown in Figure 1 that has been designed with various thickness mainly to reduce the weight. With non-uniform thickness, the springback behavior becomes more complex and difficult to be predicted.

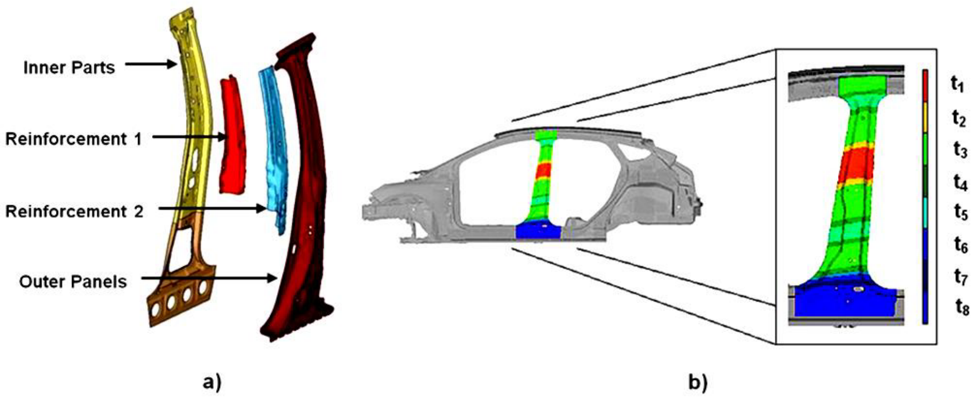

Fig. 1. Illustration of B-Pillar component; a) B-Pillar parts, b) Partition of B-Pillar with various thickness [3].

There are various steps taken to compensate the springback. Some researchers had study the effect of the process parameter to springback behaviour. Nasrollahi & Arezoo [4] found that springback phenomenon can be separated into two categories. First are factors which are more related to material issue such as Young's modulus, yield stress, strength coefficient, strain hardening, Poisson's ratio and anisotropic coefficient. Second factor are factors which are related to the bending process like tooling geometry, clearance, pad force and etc. There are various studies dealing with these parameters and their effect on springback. According to Thipprakmas [5], springback is highly affected by material thickness. While in spring-go, the bending angle has the major influence and closely followed by the material thickness. Thin material provides lighter structure but unable to prevent the presence of the springback. Deng et al. and Vasudevan et al. [6], [7] have investigated the influence of various parameters on springback for sheet metals during air v-bending. They concluded that most parameters affecting springback are identified thickness, orientation, punch travel (stroke), punch radius, die opening and punch velocities. Nandedkar [8] concluded that sheet thickness plays a very important parameter affecting springback and residual stresses. Han et al. [9] found that the springback will reduce as the forming temperatures range between 100°C to 200°C. In other study by Chikalthankar et al. and Ján et al. [10], [11], found that the greater bend depth causes higher bending angle and the higher bending result in higher amount of springback.

Traditional experimental design procedures are complicated, time consuming, and costly. Traditional trial-and-error method fails to provide an overall planning for the parameters. In general, a large number of experimental works must be conducted when the number of process parameters increases. The Taguchi method is used as a tool in designing experiments to avoid the need to conduct numerous experiments [12]. Here, Taguchi method are very useful to study the effect of many factors (variables) on the desired quality characteristic economically.

There have been consider a lot of studies on springback with uniform section, but is still lacking that involved thickness changes (non-uniform section). By knowing the effect of the thickness,variation of the thickness and other process parameter to the springback behaviour, the springback may be predicted and controlled. This paper focus on the optimization of the certain parameters to the springback pattern via v-bending method using Taguchi method.

2 Methodology

2.1 Selection of the springback parameters and their levels

There are 6 sets of specimen with different thickness ratio as listed in Table 1. Here, thickness ratio can be defined as a ratio of minimum thickness to the maximum thickness. The feasible space for the experiment parameters was defined by varying the thickness range in the range of 2.60 to 3.00 mm, the alignment of the puncher in the range 7mm to 9mm, punch stroke in the range 3 m to 7 mm, annealing temperature in the range 24 °C (RT) to 300 °C and rolling direction in the range of 0° to 90°. The other two parameters were selected as shown in Table 1.

Table 1. Springback parameter and their levels.

Factor	Parameters	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
A	Thickness Ratio	1 (3.00mm)	0.985 (2.96mm)	0.975 (2.93mm)	0.947 (2.84mm)	0.907 (2.72mm)	0.871 (2.61mm)
B	Stroke (Bend Angle)	3 mm	5 mm	7 mm	-	-	-
C	Annealing Temp.	24°C (RT)	150°C	300°C	-	-	-

In this study, an L_{18} ($6^1 \times 3^2$) orthogonal array with three column and eighteen rows was appropriate and used in this study. The experimental layout for springback parameters using L_{18} OA is shown in Table 2. Each row of this table represents an experiment with different combination of parameters and their levels.

2.2 Specimen preparation

For this experiment, the aluminum strip has to be cold formed into non uniform profile (curved shape) and cut into desired dimension as shown in Figure 2, which has various thickness and the data summarized in Table 3. “X mm” indicate the length of curved area and the measured area. For the deformation, the die and puncher were made from D2 steel material and the process was performed using the 100 Tonne mechanical press forging machines. The specimen cut into desired dimension at 50 x 20 mm. There are 6 sets of specimen with different thickness ratio as listed in Table 3. Here, thickness ratio can be defined as a ratio of minimum thickness to the maximum thickness.

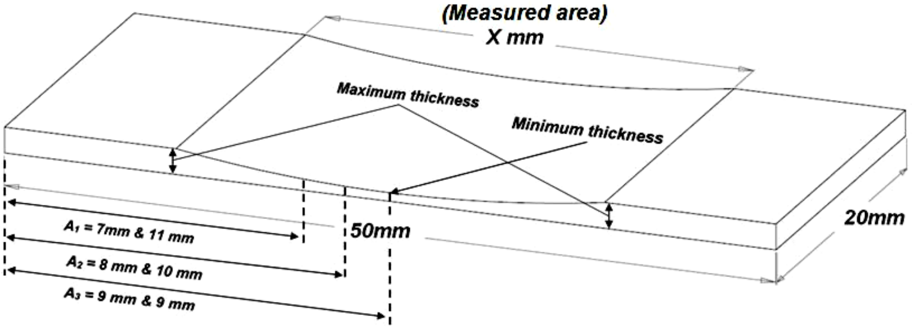

Fig. 2. Aluminium strip for non uniform profile (Curved shaped).

Table 2. Experimental layout based on an L_{18} orthogonal array.

Experiment Number	Parameter			Parameters Setting
	Thickness Ratio (A)	Bend Angle (B)	Annealing Temp (C)	
1	1	3	24 (RT)	A1 B1 C1
2	1	5	150	A1 B2 C2
3	1	7	300	A1 B3 C3
4	0.985	3	24 (RT)	A2 B1 C1
5	0.985	5	150	A2 B2 C2
6	0.985	7	300	A2 B3 C3
7	0.975	3	150	A3 B1 C2
8	0.975	5	300	A3 B2 C3
9	0.975	7	24 (RT)	A3 B3 C1
10	0.947	3	300	A4 B1 C3
11	0.947	5	24 (RT)	A4 B2 C1
12	0.947	7	150	A4 B3 C2
13	0.907	3	150	A5 B1 C2
14	0.907	5	300	A5 B2 C3
15	0.907	7	24 (RT)	A5 B1 C1
16	0.871	3	300	A6 B1 C3
17	0.871	5	24	A6 B2 C1
18	0.871	7	150	A6 B3 C2

Table 3. Aluminium strip data

Set	Length (mm)	Wide (mm)	Minimum Thickness (mm)	Thickness ratio
1.	50	20	3.00	1.000
2.	50	20	2.955	0.985
3.	50	20	2.925	0.975
4.	50	20	2.841	0.947
5.	50	20	2.721	0.907
6.	50	20	2.613	0.871

2.3 Experimental setup

In the measurement of angle after loading, the die valley radius, punch radius and the die opening are constant at 90°, 2 mm and 32 mm respectively. The die radius and punch radius is assume to be equal in this study. The bend radius is 10, 17 and 24 degree at 3, 5 and 7mm stroke respectively. To validate the springback measurement by profile projector, an Alicona Infinite Focus Machine (IFM) is used to as shown in Figure 3. The results in term of average of springback were obtained after conducting the v-bending test for all specimens. The measurement data by both method show less difference in range between -0.0435 to 0.0105.

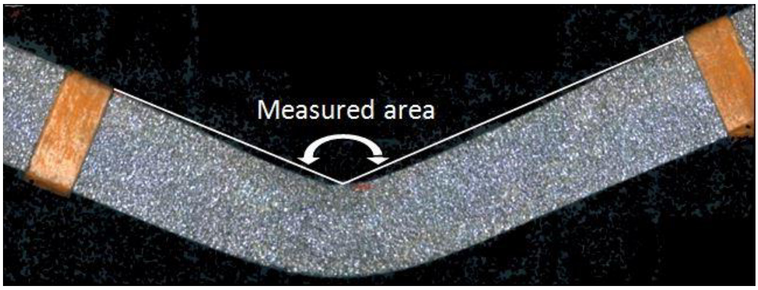

Fig. 3. Springback measurement using Alicona Infinite Focus Machine (IFM).

3 Results and discussion

3.1 V-bending experiment

Measurement of springback can be described as a difference between the angle after loading and after unloading. In the v-bending experiment, observations were made at different stroke. The maximum stress is different for each annealing temperature where specimens with no heat treatment have the highest maximum stress that is 700Mpa approximately, followed by 600 Mpa for 150°C temperature and 300 Mpa for 300°C. The results of this experiment are summarized in Table 4.

Strain is also play significant role in springback result where the increasing number of strain hardening will increase the springback. Figure 4 shows the stress strain behavior of the material for maximum stroke, 7mm. Strain hardening (also called work-hardening or cold-working) is the process of making a metal harder and stronger through plastic deformation. This scenario explains why the flow stress increases with the increase of the axial strain amount. Strain hardening increases the hardness of the section with a minimum thickness. Figure 5 shows the relation between the thickness of a workpiece and Vickers hardness pattern. The average values are obtained from five readings at the same location. Strain also plays a significant role in the occurrence of springback; increased strain hardening increases the springback. Strain hardening constraint, which known as strain hardening index is represented by n. This constant is used to calculate stress-train behavior in work hardening. The work-hardening expression can be determined at higher strain values which in the range plasticity zone. By changing the value of true stress-strain on the curve to logarithmic graph the value of slope, slope of n (strain hardening exponent) and an intercept of log K (K as strength coefficient value) can be obtained. Generally, if n value is 0 it is shown that the material is perfectly plastic solid and if the value is 1 it represents the material is totally elastic. Figure 6 shows the relation between effect of annealing temperature of specimen and Vickers hardness number. Figure 7 show the values known as the strain-hardening index for rolling direction of 0°, 45° and 90° which are 0.30, 0.284 and 0.271 respectively. The results almost coincided with studies made by Dwivedi et al [13].

Table 4. Experimental result for v-bending on an L_{18} orthogonal array.

Experiment	Parameter Setting	% Springback 1	% Springback 2	S/N Ratio
1	A1 B1 C1	0.0041	0.0103	41.016
2	A1 B2 C2	0.0189	0.0194	33.671
3	A1 B3 C3	0.0497	0.0361	26.904
4	A2 B1 C1	0.0159	0.0187	34.501
5	A2 B2 C2	0.0159	0.0108	36.254
6	A2 B3 C3	0.0101	0.0146	37.105
7	A3 B1 C2	-0.0029	0.0008	63.271
8	A3 B2 C3	0.0109	0.0102	38.282
9	A3 B3 C1	0.006	0.0107	40.011
10	A4 B1 C3	-0.0014	0.0002	59.359
11	A4 B2 C1	0.0181	0.0192	33.906
12	A4 B3 C2	0.0296	0.0275	30.408
13	A5 B1 C2	0.0089	0.0037	41.105
14	A5 B2 C3	0.0087	0.0071	40.310
15	A5 B1 C1	0.0304	0.0248	30.624
16	A6 B1 C3	0.0049	0.0053	43.439
17	A6 B2 C1	0.0121	0.0129	37.030
18	A6 B3 C2	0.0353	0.0434	27.754

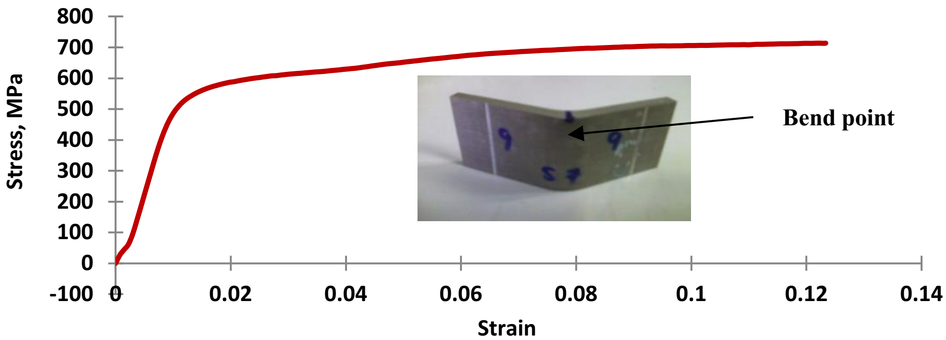

Fig. 4. The stress strain behaviour of the material.

3.2 Regression analysis

The correlation between factors (thickness ratio, bend angle, annealing temperature) and response (springback percentage) were obtained by multiple linear regressions. The statistical software Minitab was used to derive the regression Eq. (1) with $R^2 = 0.7418$.

$$\text{Springback percentage} = 0.01252 + 0.0(A6) - 0.00869(A5) - 0.00493(A4) - 0.01330(A3) - 0.00585(A2) + 0.00137(A1) + 0.0(B1) + 0.00676(B2) + 0.01968(B3) + 0.0(C1) + 0.00150(C2) - 0.00385(C3) \quad (1)$$

In multiple linear regression analysis, R^2 is the regression coefficient ($R^2 > 0.90$) for the models. It indicates that the fit of the experiment is satisfactory. In this case, the parameters numbers influenced the regression coefficient value as shown in Figs. 5-7. Since this model have mixed level of parameters, 0.7418 is possible for this study and coincide with analysis done by Buang et al. [14].

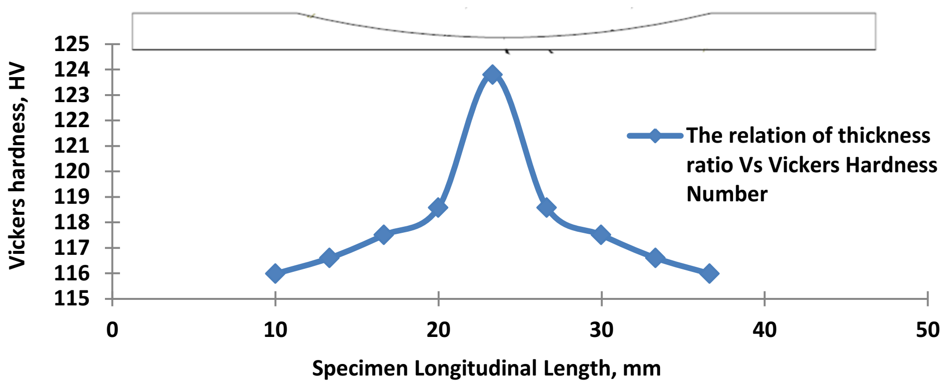

Fig. 5. The relation of Thickness Vs Vickers Hardness Number.

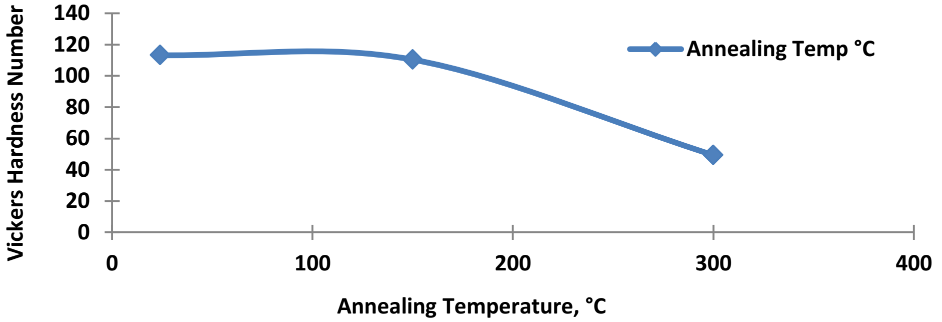

Fig. 6. The relation of Annealing Temperature Vs Vickers Hardness Number.

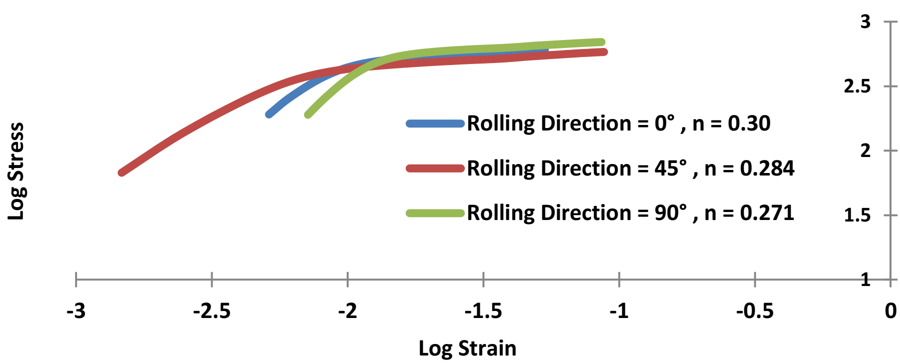

Fig. 7. Stress-strain in various rolling direction in logarithmic diagram taking *n* as parameter.

3.3 Analysis of the signal-to-noise ratio (S/N ratio)

The signal to noise ratio (S/N Ratio) is meant to be used as a measure of the effect of noise factor on target characteristics. The springback values measured from the experiments and their corresponding S/N ratio value are listed in Table 4. The springback response table for thickness ratio, bend angle and annealing temperature was created in the integrated form and the result shown in Table 5. Based on the Figure 8, the optimal performance for the percentage of springback when the parameter setting of specimen is A3, B1, C3, Table 5 show the effect of the process parameters on the springback percentage values. Based on the Table 5, the delta for bend angle (stroke), is the highest which is 14.98. The bend angle (stroke) is the main parameter that affects the springback percentage in this experiment. The results are in agreement with studies that have been done by Abdullah & Samad [15].

Table 5. S/N ratio value for springback percentage by factor level.

Level	Thickness Ratio	Bend Angle	Annealing Temperature
1	36.07	47.12	36.18
2	37.35	36.58	38.74
3	41.22	32.13	40.9
4	47.19		
5	35.95		
6	33.86		
Delta	13.32	14.98	4.72
Rank	2	1	3

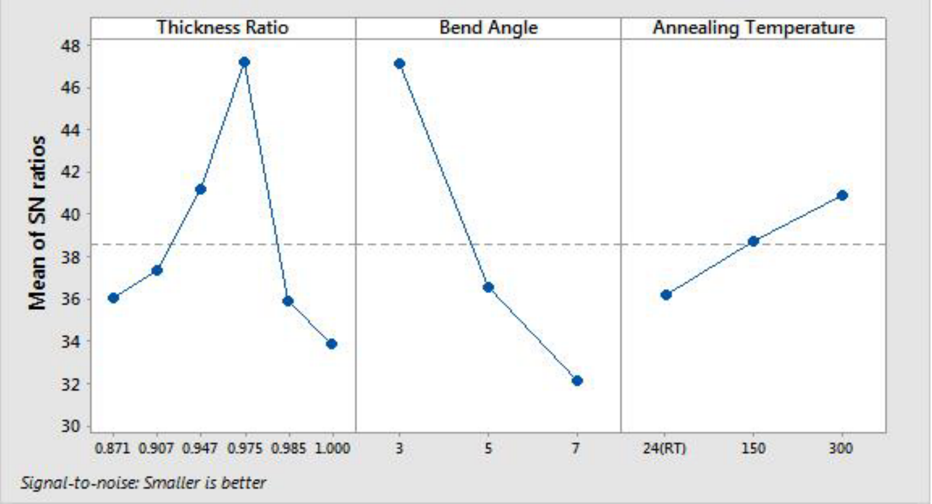

Fig. 8. Effect of process parameters on springback percentage.

3.4 Analysis of variance (ANOVA)

The main goal of ANOVA is to evaluate the experimental error and test its significance. The result of ANOVA and response result for S/N ratio smaller-is-better is represented in Table 6. Based from the result, the F value for the parameter (bend angle) is 7.94 which is the highest. It means that the change of the parameter has significant effect on the percentage springback. The P-value reports the significance level (suitable and unsuitable). The P-value for parameter B is 0.013± which lower than 0.05. So, effect parameter B is significant to the result of the experiment. The percentage number on Table 6 depict that the parameter B, stroke (bend angle) have significant effects on springback percentage. From the table, the contribution of parameter B is 51.25%, parameter A 19.04% and parameter C 3.89%.

3.5 Confirmation test

The final stage in verifying the result drawn based on Taguchi design approach is confirmation test. It has a maximum and minimum value between which the observed value should fall. From Table 7, confidence interval comes out to be ± 0.0005; hence values of spring back for confirmation experimental runs should fall within the range -0.001466± 0.0005 i.e. -0.001966 to 0.000996. Table 8 shows a comparison between the estimated value of springback percentage at optimum condition as shown in figure 8 and the experimental value. A small difference (0.000213%) can be observed between these values. This indicates that the experimental value is close to the estimated value. Therefore, this verifies that the experimental result is highly correlated with the estimated result.

Table 6. ANOVA result.

Symbol	**Parameter**	**Degree of freedom, DOF**	**Sum of Square, SS_T**	**Mean Square, SS_m**	**F-Value**	**P-Value**	**ρ % Contribution**
A	**Thickness Ratio**	5	0.000446	0.000089	1.18	0.397	19.04
B	**Bend Radius**	2	0.0012	0.0006	7.94	0.013	51.25
C	**Annealing Temperature**	2	0.000091	0.000046	0.6	0.57	3.89
Error		8	0.000604	0.000076			25.82
Total		17	0.002341				100

Table 7. Confidence interval.

Response	No. of samples	Mean	Standard Deviation	C.I
Springback Percentage	1	-0.001466	0.0008332	± 0.0005

Table 8. Optimal combination of parameters and their level.

	Estimation	**Experiment**	**Difference**
Level	A3 B1 C3	A3 B1 C3	
Springback percentage, %	-0.001466	-0.001253	0.000213
S/N ratio	57.9865	-	

4 Conclusions

In this study has discussed an application of Taguchi method for investigating the effect of parameters on the springback behaviour of Aluminium 6061-T6 strip with non-uniform thickness. Statistically designed experiments based on Taguchi method were performed using L_{18} orthogonal arrays to analyze the springback behaviour as response variable. Conceptual S/N ratio and ANOVA approaches for data analysis resulting similar conclusion. The regression coefficient, R^2 is equal to 0.7418. Since this an L_{18} $(6^1 \times 3^2)$ orthogonal array is a combination of multi level parameters, possibility to achieve ≥0.90 is difficult. The optimum percentage of springback is -0.001466 with S/N ratio of 57.9865. Stroke (bend angle) is the most significant parameter while annealing temperature is the least significant parameter. The contribution of parameter to percentage of springback is Bend radius (51.25%), thickness ratio (19.04%) and annealing temperature (3.89%).

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