OPTIMIZATION OF PROCESS PARAMETERS IN SINGLE POINT INCREMENTAL FORMING OF AA 6063-O ALLOY

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Abstract— Incremental forming is a special technique that offers flexibility and cost-effectiveness in the metal forming process, requiring no high capacity presses or set of dies, thus meeting the ever increasing demand for low volume production and rapid prototyping. In this paper, the effect of process parameters such as feed rate, spindle speed, step size and tool diameter on wall angle was investigated. Aluminum sheet of grade Al 6063-O with 1 mm thickness is used as a work piece. Here an L9 (34) orthogonal array is used to plan the experiments and analyze the results. Experimental results were tested by analysis of variance (ANOVA) technique. The results indicated that a maximum wall angle of 55^0 can be achieved through the incremental forming. The forming limit diagram is also drawn for incremental forming.

Index Terms—Incremental forming, Design of experiment, Optimization, AA 6063**.**

I. INTRODUCTION

Traditionally a sheet-metal component is manufactured by using dies and punches. Because of the high cost of dies and punches, the traditional manufacturing method is adequate only for mass production. The production of customized products, the increasing demand of process flexibility and the necessity to reduce the time to market the products are probably the most significant requirements nowadays. For these reasons, the industrial applications have to be economically justified with a large volume production. Further, stamping cannot fully satisfy the demand of flexibility. These considerations clearly show that the current metal stamping processes may maintain a relevant role in the modern production routings only if cheaper and more flexible technologies are developed. Hence, in the last few years, incremental forming has been introduced as an alternative to the money consuming stamping technology. Here, the final component shape is achieved by the relative movement of a rotational hemispherical tool which follows computer generated tool paths with respect to the blank, without using any dedicated dies to achieve the shape. Its flexibility and low-cost tooling render SPIF more economical than spinning, which was considered as an economical process to produce axisymmetric components in small batches.

Several studies have been carried out on the formability in Single Point Incremental Forming (SPIF). Leszak patented a process of incrementally deforming a sheet [1]. Kim and Park investigated the effect of some process parameters on the formability of an aluminum sheet [2]. Shanmuganatan et al. performed finite element and experimental analyses on profile forming of conical component and found the thinning variation of the component [3]-[4]. Ham and Jeswiet showed the methodology for developing Forming Limit Diagram for SPIF [5]-[6]. Hussain et al. suggested a novel method to test the thinning limits of sheet metals in negative incremental forming. He also studied the effect of the curvature of a part’s generatrix on the formability of an aluminum sheet [7]-[8] Strano et al. also describe the effect on formability of various process parameters [9]. Ambrogio et al. proposed an integrated numerical/experimental procedure in order to limit the shape defects between the obtained geometry and the desired one. He also investigated the influence of the process parameters on accuracy through a reliable statistical analysis [10]-[11]. Myoung- Sup Shim et al. studied the formability of aluminum sheet by imposing different tool paths and found the forming limit curve [12]. Durante et al. evaluated the influence of tool rotation, both in terms of speed and direction of rotation [13].

The movement of the SPIF tool over the surface of the sheet causes a highly localized deformation. SPIF results in higher metal formability, when compared to conventional forming process. The following basic assumptions have been made during the modeling of the SPIF process:

a. The material is isotropic and elastic strains are neglected.

b. The periphery of the sheet is rigidly clamped.

c. Homogeneous deformation exists throughout the process.

II. EXPERIMENTAL DETAILS

The basic concept of the single point incremental forming process is to obtain the desired shape of the product of the relative movement of a simple hemispherical tool in relation to the sheet blank, without the use of dies.

Table 1. Chemical composition of AA6063 (in weight %)

Si	0.483	Mn	0.063
Pb	0.017	Zn	0.114
Fe	0.353	Mg	0.690
Cu	0.075	Cr	0.012
Ni	0.072	Al	Bal

Fig. 1.a Truncated cone to be formed

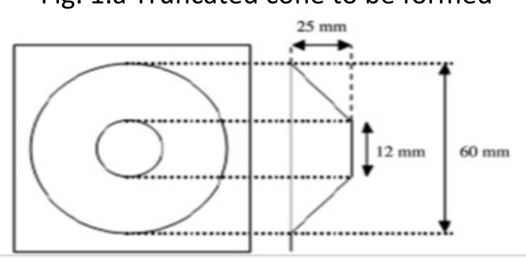

Fig. 1.b Dimensions of the truncated cone

Table 2. Process parameters and their levels

Factor	Process parameter	Unit	Levels		
			1	2	3
A	Feed rate	mm/min	1000	1500	2000
B	Spindle speed	rpm	2000	3500	5000
C	Step size	mm	0.2	0.5	0.8
D	Tool diameter	mm	5	10	15

In this process, a layer of constant depth in axial direction is formed by an in-plane movement of the tool. On completion of each layer, the tool moves down with a small increment along the axis, to process the subsequent layers till the completion of the process.

The single point incremental forming is carried out on a three axes CNC vertical milling machine. The material used in this study was an Aluminium alloy, AA 6063- O sheet 200 mm in length, 200 mm in width and 1 mm in thickness. The chemical compositions are listed in Table 1.

Hemispherical head tools of three sizes were used: 5, 10 and 15 mm in diameter were made of H13 tool steel and were hardened up to 60 HRC. The truncated cone, which is taken as a model for study as shown in Fig. 1.a and 1.b is thus, generated using this process. It has been stated that the tool diameter, spindle speed, feed rate step size, forming angle, sheet thickness and shape of the component are the main factors that affect the wall angle of SPIF. In this present work, the tool diameter, spindle speed, feed rate and step size were considered to be variables in the optimization of SPIF process.

Trial experiments were performed to identify the working range of the selected parameters. The feasible limits of these parameters are determined on the basis that no defects are formed in the components during SPIF. The parameters and its levels are shown in table 2.

A coordinate measuring machine is used to measure the wall angle at 22 mm depth of the profile from the clamping section.

III. RESULTS AND DISCUSSIONS

3.1. *Signal to noise(S/N) ratio*

Taguchi's method uses the Signal to Noise (S/N) ratio in place of the mean value to convert the experimental results in a value for the evaluation characteristic in the optimum setting analysis. Some measurable responses to the analysis output during the operation of any engineering system or process are called performance characteristics [14]. The quality of the formed cones is investigated by considering the wall angle as the main characteristic feature considered in this investigation describing the quality of the welded joints. In order to find the influence of process parameters on the response, the Signal to Noise ratio and means for each process parameter were calculated. In this current work, the S/N ratio was chosen according to the principle of 'the larger-the better' characteristics, which is shown in equation (1).

$$(S/N)_{HB} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{H_i^2}\right) \quad (1)$$

Where n is the number of the repetitions and Hi is the value of the wall angle of the test on that trail. The process parameters, experimental wall angle and signal-to-noise (S/N) ratio are given in Table 3.

Table 3. L9 orthogonal array with response

Ex pN o	Input Parameters				Wall angle (Respons e)	S/N ratio
	A	B	C	D		
	mm/m in	rp m	m m	m m	Degrees (0)	Db
1	1000	200 0	0. 2	5	55	34.80 73
2	1000	350 0	0. 5	10	52	34.32 01
3	1000	500 0	0. 8	15	46	33.25 52
4	1500	200 0	0. 5	15	43	32.66 94
5	1500	350 0	0. 8	5	46	33.25 52
6	1500	500 0	0. 2	10	52	34.32 01
7	2000	200 0	0. 8	10	43	32.66 94
8	2000	350 0	0. 2	15	51	34.15 14
9	2000	500 0	0. 5	5	41	32.25 57

Table 4. Mean response table for S/N ratio

Levels	Feed rate	Spindle speed	Step size	Tool diamete r
	(mm/min)	(rpm)	(mm)	(mm)
1	34.13	33.38	34.4 3	33.44
2	33.41	33.91	33.0 8	33.77
3	33.03	33.28	33.0 6	33.36
min-max	1.10	0.63	1.37	0.41
rank	2	3	1	4

Table 5. Mean response table for experimental data

Levels	Feed rate (mm/min)	Spindle speed (rpm)	Step size (mm)	Tool diameter (mm)
1	51.00	47.00	52.67	47.33
2	47.00	49.67	45.33	49.00
3	45.00	46.33	45.00	46.67
min-max	6.00	3.33	7.67	2.33
rank	2	3	1	4

The mean response of S/N ratio and experimental data for each level of the process parameter are given in table 4 and table 5.

3.2. *Analysis Of Variance*

Analysis of variance (ANOVA) test was performed to identify the statistically significant process parameters [15]. This analysis was carried out for a level of significance of 5 %, i.e. for 95% confidence level. The ANOVA results of S/N ratio and the means (both initial and final) for wall angle are given in Table 6, Table 7, Table 8 and Table 9 respectively. The frequency test (F-test) is utilized in statistics to analyze the significant effects of the parameters, which form the quality characteristics.

Since the error is zero in table 6 and table 8, the significant factors cannot be found out. Hence, the minimum contributed factor's sum of squares can be pooled into error term i.e. sum of squares of tool diameter is pooled into error term in table 7 and table 9, and F-test is conducted. Since $F_{0.05,2,8}$ =4. 46, factors A and C are only significant at the 5 % level of significance from table 7 and table 9.

Table 6. ANOVA (initial) of S/N ratio of wall angle

Factor	Process Parameters	Sum of squares	Degrees of freedom	Mean sum of squares	F-test
A	Feed rate	1.87388	2	0.93694	-
B	Spindle speed	0.68794	2	0.34397	-
C	Step size	3.67516	2	1.83758	-
D	Tool diameter	0.28481	2	0.14240	
Error (pure)		-	-	-	
Total		6.52179	8		

Table 7. ANOVA (final) of S/N ratio of wall angle

Factor	Process Parameters	Sum of squares	Degrees of freedom	Mean sum of squares	F-test
A	Feed rate	1.87388	2	0.93694	6.57
B	Spindle speed	0.68794	2	0.34397	2.41
C	Step size	3.67516	2	1.83758	12.90
Error (Pooled)		0.28481	2	0.14240	
Total		6.52179	8		

Table 8. ANOVA (initial) of means for wall angle

Factor	Process Parameters	Sum of squares	Degrees of freedom	Mean sum of squares	F-test
A	Feed rate	56.000	2	28.000	-
B	Spindle speed	18.667	2	9.333	-
C	Step size	112.667	2	56.333	-
D	Tool diameter	8.667	2	4.333	
Error (pure)		-	-	-	
Total		196.000	8		

Table 9. ANOVA (final) of means for wall angle

Factor	Process Parameters	Sum of squares	Degrees of freedom	Mean sum of squares	F-test
A	Feed rate	56.000	2	28.000	6.46
B	Spindle speed	18.667	2	9.333	2.15
C	Step size	112.667	2	56.333	13.00
Error (pooled)		8.667	2	4.333	
Total		196.000	8		

Table 10. Percentage Contribution of Process Parameters

Process Parameters	Feed rate mm/min	Spindle speed rpm	Step size mm	Tool diameter mm
% Contribution	29	10	57	4

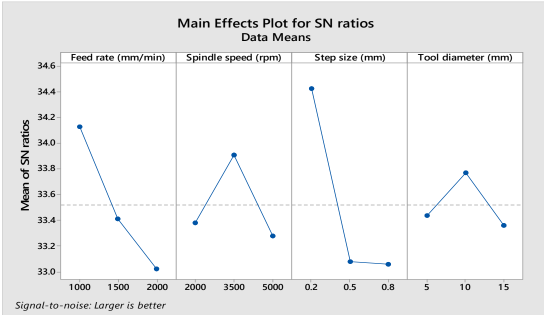

Fig.2.a Main effects plot for S/N ratio

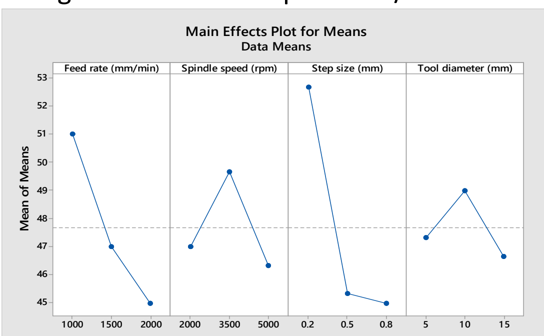

Fig.2.b Main effects plot for wall angle

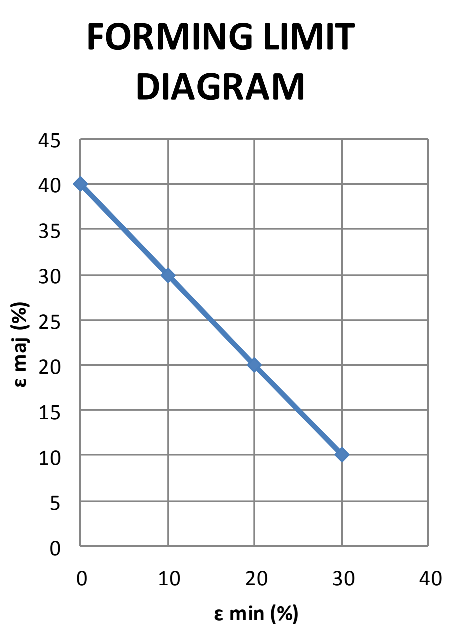

Fig. 3 Forming limit diagram

The portion of the total variation observed in an experiment attributed to each significant factor and/or interaction is reflected in the percentage of contribution. The percentage of contribution is a function of the sum of squares for each significant item. It indicates the relative power of a factor and/or interaction to reduce the variation. If the factor and/or interaction levels are controlled precisely, then the total variation could be reduced by the amount of the percentage of contribution. The percentage of the contribution of the tool pin profile, transverse speed and welding speed is shown in table 10.

3.3. *Determination of optimum factor level combination*

Fig 2. Shows four graphs, each of which represent the mean response and the mean S/N ratio for the feed rate, spindle speed, step size and tool diameter. The values of the graphs have been tabulated in Table 4 and Table 5. Based on the highest values of the S/N ratio and mean values (Fig 2.a and 2.b), the overall optimum process parameters for wall angle are A1, B2, C1 and D2.

After the optimum level has been selected, one could predict the optimum wall angle using the following equation [16] which is shown in equation (2).

$$W_{predicted} = W_m + \sum_{i=1}^{n} (W_0 - W_m) \quad (2)$$

W_m is the mean response or the mean S/N ratio, W0 is the mean response or mean S/N ratio at optimal levels and n is the number of main design parameters that affect the quality characteristics. Substituting the values in Equation 2, the predicted wall angle value is 56^0. The highest wall angle achieved was 55^0 which was within the confidence limit.

The forming limit diagram is drawn for incremental forming of AA 6063-O alloy which is shown in Fig. 3. Here the graph is plotted with minor strain percentage (ε_{min} (%)) as x-axis and major strain percentage (ε_{maj} (%)) as y-axis. The graph obtained here is a straight line which is different from conventional forming processes. The region below the straight line is safe region and the region above it is unsafe region.

IV. CONCLUSION

In this investigation, AA 6063-O alloys were successfully formed incrementally. The results can be summarized as follows:

• The L9 Taguchi orthogonal designed experiments of SPIF of AA6063-O were successfully conducted.

• The percentage of contribution of SPIF process parameters was evaluated. It is found that the feed rate, spindle speed, step size and tool diameter contributes 29%, 10%, 57% and 4% respectively

• Feed rate of 1000 mm/min, spindle speed of 3500 rpm, Step size of 0.2 mm and tool diameter 10 mm provides higher wall angle.

• It was observed that the experimental results were close to the predicted values and they are falling within the confidence limits.

• The forming limit curve in SPIF is different from that in other conventional forming processes. It appears to be a straight line with a negative slope in the positive region of the minor strain in the forming limit diagram.

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