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Influence of process parameters on surface roughness and forming time of Al-1100 sheet in incremental sheet metal forming

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ABSTRACT

Product quality and production time are critical constraints in sheet metal forming. These are normally measured in terms of surface roughness and forming time, respectively. Incremental sheet metal forming is considered as most suitable for small batch production specifically because it is a die-less manufacturing process and needs only a simple generic fixture. The surface roughness and forming time depend on several process parameters, among which the wall angle, step depth, feed rate, sheet thickness, and spindle speed have a greater impact on forming time and surface roughness. In the present work, the effect of step depth, feed rate and wall angle on the surface roughness and forming time have been investigated for constant 1.2 mm thick Al-1100 sheet and at a constant spindle speed of 1300 rpm. Since the variable effects of these parameters necessitate multi-objective optimization, the Taguchi L9 orthogonal array has been used to plan the experiments and the significance of parameters and their interactions have been determined using analysis of variance (ANOVA) technique. The optimum response has been brought out using response surfaces. Finally, the findings of response surface method have been validated by conducting additional experiments at the intermediate values of the parameters and these results were found to be in agreement with the predictions of Taguchi method and response surface method.

Keywords: Incremental sheet metal forming; surface roughness; productivity; forming time; Taguchi; ANOVA.

INTRODUCTION

Incremental sheet metal forming (ISF) is suitable for small batch production and new product development. Flexibility in the manufacturing of asymmetric parts and low tool cost are the two core motives for using ISF in industries. Localized plastic deformation imposed by a tool helps in forming the sheet to the desired shape [1] in ISF. Single point incremental forming (SPIF) is one of the ISF forming techniques in which the shape of the part is controlled by the axis movement of computer numerical control (CNC) machine or any robot. In this process, the quality of the part surface is an important concern for the customer. Surface roughness is one of the parameters which help in improving the quality of the surface. In ISF, there are many parameters which affect surface roughness directly or indirectly. These parameters include feed rate, spindle speed, step depth, cutting condition, tool material, sheet material, and machine vibration. But the last four parameters are uncontrollable parameters. Various methods have been proposed in the literature to study roughness and quality of the surface [2]. Effect of tool depth increment and spindle speed variation on the surface roughness of Al3003 sheet was investigated and roughness was measured using white light interferometer [3]. It was found that spindle speed has little effect on roughness. Tool path has also a great impact on surface roughness. Tool path is a function of time, step depth and scallop height. By varying these three parameters tool path has been optimized for the quality surface finish in two point asymmetric incremental forming[4]. Thinning analysis and formability analysis has been done by varying wall angle and keeping other parameters constant [5]. Other parameters like tool radius, vertical step and feed rate were varied to check the change in surface quality[6]. Ten points mean roughness, absolute roughness and RSM values were checked experimentally as well as analytically. Effect of parameters like vertical step, feed rate, spindle speed, tool diameter on surface roughness was investigated on Al1050 sheet metal. It was found that tool with larger diameter has a positive effect on surface roughness but an adverse effect on accuracy. The lower value of step depth gave better surface finish and higher value of feed rate and spindle speed has a positive effect on accuracy and surface roughness of the part[7,8]. Using Response surface methodology surface quality and forming time were optimized by varying three input parameters i.e. spindle speed, feed rate and tool size on AA7075 sheet[9]. Wall thickness and surface roughness were predicted as a function of three parameters using a second order quadratic model. By changing sheet thickness along with feed rate, step depth and tool diameter, surface roughness changes[10]. Impact of these four parameters was predicted by response surface methodology with multi-objective function and Box-Behnken design. Sheet thickness had maximum influence on roughness and then step down. Feed rate and tool diameter had little effect on surface quality. Many optimisation techniques have been employed to optimise process parameters till the date. Artificial neural network (ANN), support vector regression (SVR) and genetic algorithm (GA) were used to optimise parameters in ISF [11]. ANN and SVR performed better than GA and predicted results were in very good agreement with the experimental value. Sheet thickness is also a key parameter for formability and forming time. Optimum Spindle speed and sheet thickness for achieving maximum formability and in minimum forming time for AA-3003 sheet was reported [12,13]. Surface roughness decreases with increase in tool radius, a decrease in step depth and a decrease in sheet thickness. Lubrication has also influence on surface roughness, dry and cool lubricant increases roughness as compared to grease [14,15]. Roughness value also depends on tool path direction and is better in tool-advancing direction than perpendicular one [16]. Tool shape and tool-sheet contact condition change surface quality[17] . Vertical pitch and feed rate have more effect on forming time than tool diameter [18].

Very few studies have been done on commercial aluminum Al-1100 in ISF. The effect of the combination of three process parameters, namely, wall angle, feed rate and step depth for achieving good surface finish and minimum forming time has not been studied previously. Therefore, the novelty in the present work is optimization of surface finish and manufacturing time with respect to wall angle, feed rate, step depth and their interactions in single stage incremental sheet metal forming of Al-1100. Design of experiments was carried out using the L9 orthogonal array method. These nine experiments were conducted on a CNC vertical milling machine. The results were analyzed using ANOVA and response surface method to obtain optimum process parameter settings.

THEORETICAL ANALYSIS

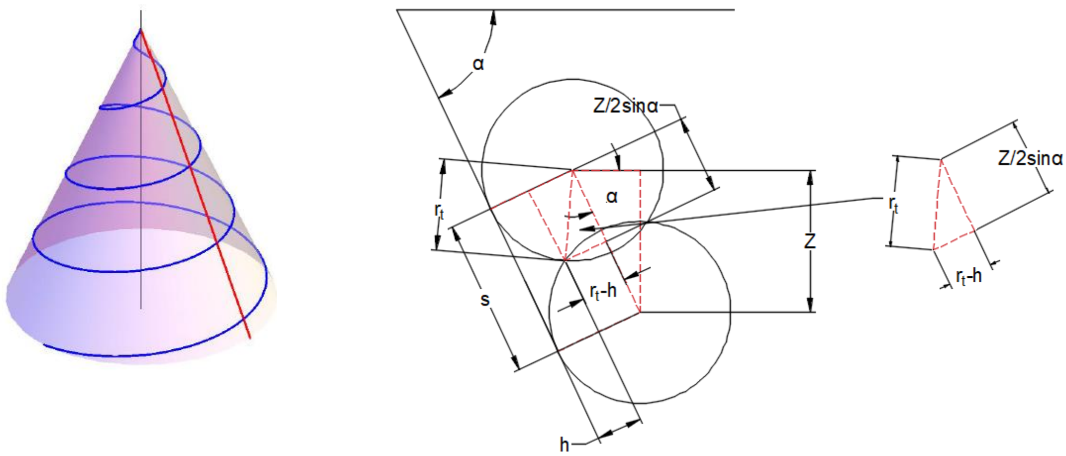
Tool Path Planning

The tool path planning for a conical spiral of the workpiece for a given wall α of alpha was derived to be as follows:

$$0 \le u \le 1 \begin{cases} z = \Delta z[i - 1 + u] \\ x = (R - z cot\alpha) cos2\pi u \\ y = (R - z cot\alpha) sin2\pi u \end{cases} \quad (1)$$

Scallop Height

The dependence of the scallop height, h, on the process parameters of tool radius (r_t), step depth (z) and the wall angle (α) is given by the Eq.(1) as per the configuration is given in Figure 1.



(a) (b)

Figure 1. (a) The spiral tool path for the conical cup part and (b) the scallop height.

From Figure 1, the relation between tool radius, scallop, step depth, and wall angle can be expressed as

$$r_t^2 = (r_t - h)^2 + \left(\frac{z}{2 \cdot \sin\alpha} \right)^2$$

$$h = r_t - \sqrt{r_t^2 - \left(\frac{z}{(2 \times \sin\alpha)} \right)^2} \quad (2)$$

where h is scallop height, r_t is tool radius; z is step depth and α is wall angle.

From Eq.(2), it can be observed that, with increases in step depth, scallop height increases but with an increase in wall angle, scallop height decreases if step depth is constant. But the increase in step depth reduces overall forming time. Similarly, if step depth has to be maintained constant throughout the sheet, scallop height will decrease with an increase in wall angle. The decrease in scallop height will increase surface quality.

Similarly, the increment in step depth will increase the undeformed area on the formed sheet as shown in Figure 2 but will reduce the overall forming time. Feed rate will vary surface quality along the tool path contour but will not affect roughness value along the wall if other process parameters are constant. From Figure 1(b), the relation between step depth, tool center distance and wall angle can be represented as follows.

$$z = s \times \sin\alpha \tag{3}$$

Where 's' is the distance between centers of the tool in two consecutive passes.

Combining Eq.(2),(3), scallop height can be represented as follows:

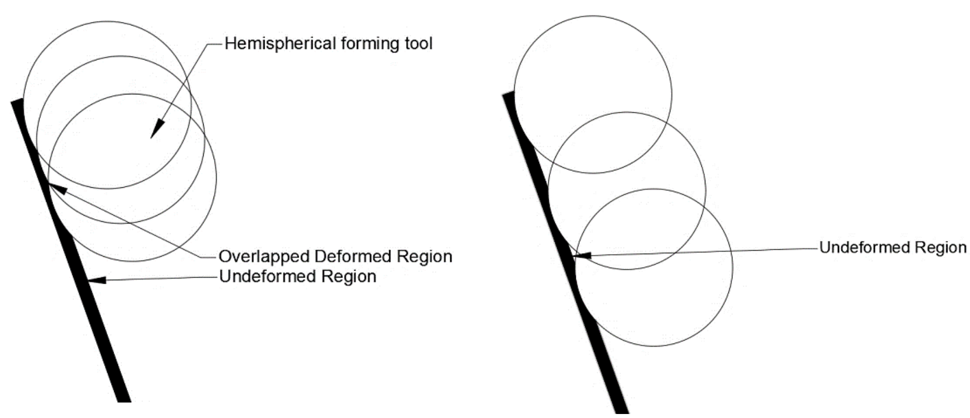
$$h = r_t - \sqrt{r_t^{\,2} - \left(\frac{s}{2}\right)^2} \tag{4}$$

In the above relation, it can be observed that,

$$h_{(s<r_t)} < h_{(s=r_t)} < h_{(s>r_t)}$$

With an increase in distance between the tools, step depth increases which in result increases scallop height. Increase in scallop height lead to the reduced surface finish.

The increment of feed rate will not affect the surface roughness in the vertical direction but forming time can be greatly reduced by increasing feed rate due to larger tool travel in a shorter time interval. However, combined effect of all the parameters is difficult to analyze theoretically. Therefore experiments were conducted to verify the combined effect of all parameters on surface quality.



(a) (b)

Figure 2. Deformation zone due to (a) small step depth and (b) larger step depth

EXPERIMENTAL SETUP

Experiments were conducted using Fanuc-I series GX600 three axes vertical CNC milling machine. Al-1100 is a commercially used aluminum sheet which is widely used in chemical, food processing industries, hollowware, and heat exchangers due to its excellent resistance to corrosion. It is also used in applications where intrinsic formability and high corrosion resistance is needed but not high strength. In this work, a sheet of 250mm×250mm×1.2mm has been used for experiments. The sheet has been clamped on the fixture with locating pin and baking plate and both are mounted on a CNC machine table as shown in Figure 3. Larger tools are suitable for SPIF to avoid pillow effect as a contact zone between the tool and sheet increases[19]. It also helps in improving formability [20]. EN36 hemispherical tool of 15mm diameter has been used for this operation. The tool was heat treated to 60HRC and was polished with fine grade abrasive paper. Forming tool and the fixture have been shown in Figure 3. Tool and sheet surface friction was reduced by using SAE40 lubricant. Forming angle, step depth and feed rate have been varied in each operation with a constant spindle speed of 1300rpm.

Thickness, surface quality, and dimensional accuracy can be affected by tool path. So a proper tool path is an essential input in ISF to get desired output. Various tool path generation techniques have been used previously but out of all tool paths profile tool path and spiral tool path (Helical tool path) have given significant output till date. To reduce uneven scar mark in profile tool path, the helical tool path was proposed [21]. Spiral tool path was found to be more effective in strain distribution, Relative thinning, surface quality and forces [22]. So to investigate surface roughness, a spiral tool path was used in this study. 3D model has been generated using Pro E software. Spiral tool path has been generated in the form of G code and M code using CAM software. G-codes and M-codes were directly given as input to CNC machine for experiments.

After Single stage ISF experiments, the surface roughness measurement was done by using Taylor Hobson surface roughness tester shown in Figure 3. In this tester, a diamond tip stylus moves across the peaks and valleys of the surface and measures roughness. Surface roughness at 4 points along the perpendicular direction to the tool direction on a single sheet has been measured for all the sheets as shown in Figure 3. Samples were cut by EDM wire cut machine from each part. For circular geometry, samples were cut from 4 regions located at 90º relative to each other. Four measurements were recorded from each part and the average of these four measurements was calculated.

DESIGN OF EXPERIMENT

Planning and execution of experiments affect result to a great extent. Selection of parameters, no. of experiments also affects the same. In most of the cases full factorial experiments are conducted, but considering the time and cost it cannot be implemented when a number of input parameters is more. The design of the experiment is one of the effective tools to reduce the number of experiments. It can collect all the statistically significant data with less number of repetitions. This process has been successful for improving product quality and the process. Taguchi orthogonal array (OA) is one of the widely used DOE techniques. It helps in selecting the interaction which can influence the quality of the product and based on this it calculates a number of experiments. As in this study, the number of influencing parameters is three which is called three-level factors in OA, so as per OA-3^2 experiments were conducted. Forming tool diameter and spindle speed were kept constant throughout the experiment. All the 9 experiments have been conducted using vertical CNC milling machine (specifications shown above). Forming angle, step depth, and feed rate were the input in these and the value and level of these controlled parameters are shown in Table 1. The L9 orthogonal array experimental combinations between all parameters have been shown in Table 2. All the factors have been coded as A, B and C. All the three values for each factor have been coded as 1, 2 and 3. Combination of the interaction of all the levels for each factor has been tabulated in Table 2.

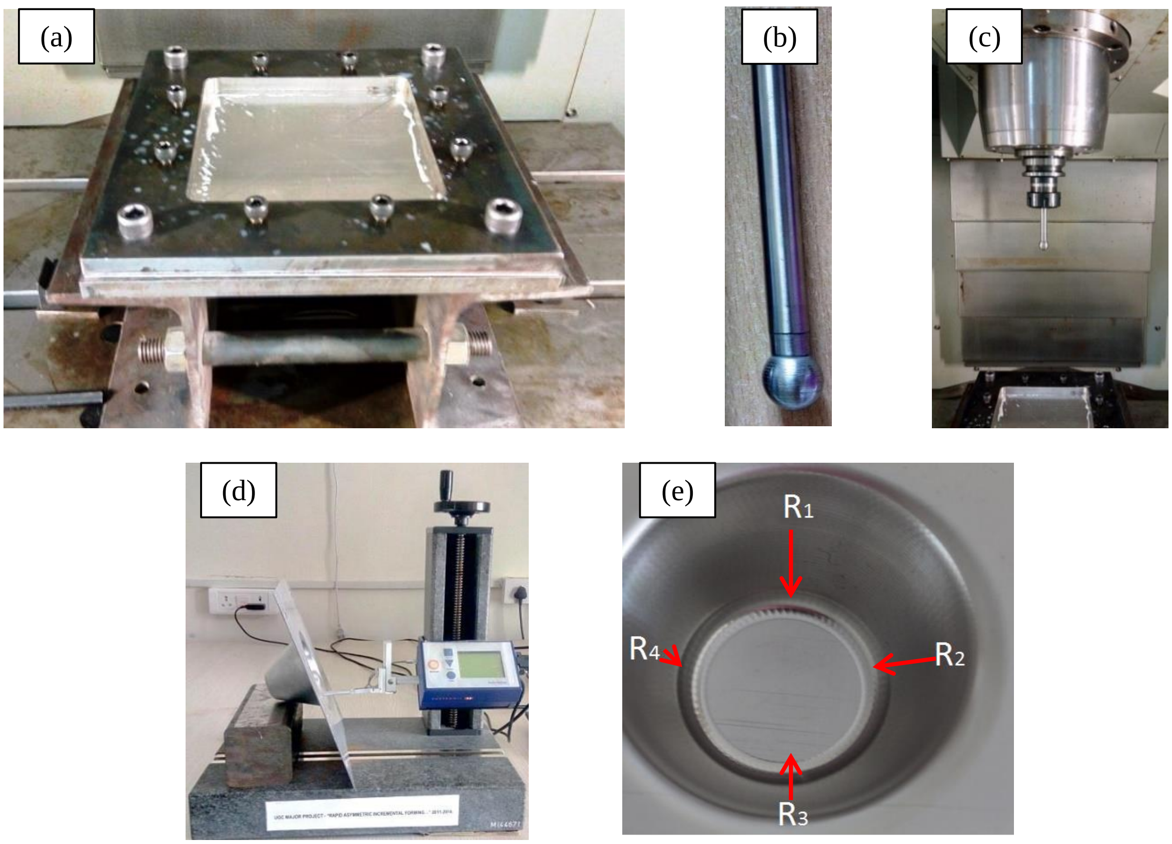


Figure 3. (a) Forming fixture, (b) forming tool, (c) the setup and (d) profilometer (e) direction of surface roughness measurement

Table 1. Level of selected control parameters

Factors	Units	Notations	Original values (Level)			Coded values (Level)		
			1	2	3	1	2	3
Forming Angle	Degree(°)	A	60	65	70	1	2	3
Step depth	mm	B	0.5	1	1.5	1	2	3
Feed rate	mm/min	C	1000	1500	2000	1	2	3

To analyze the result S/N ratio is calculated which shows both average and variation in experimental results. In this study, low forming time and better surface finish are our main objective. So smaller the S/N value better is the result. S/N ratio is given by the equation given below.

$$\frac{S}{N} = -10\log\left[\frac{1}{n}\sum_{1}^{n} y_i^{\ 2}\right] \tag{5}$$

where n is number of observations per row which is 4 for surface roughness and 1 for time in our study.
y_i= i^{th} measured roughness and time in the row.

Table 2. Experimental results (Forming Time).

Sl. No	A	B	C	Time taken (min)	S/N ratio
1	1	1	1	24.39	-27.74
2	1	2	2	8.59	-18.67
3	1	3	3	4.54	-13.14
4	2	1	2	18.15	-25.17
5	2	2	3	7.27	-17.23
6	2	3	1	9.22	-19.29
7	3	1	3	15.05	-23.55
8	3	2	1	15.21	-23.64
9	3	3	2	7.15	-17.08

The parameter interaction and effect of the same on surface texture was uncertain in Figure 4. So to check the significance of all parameters, Analysis of variance technique was chosen.

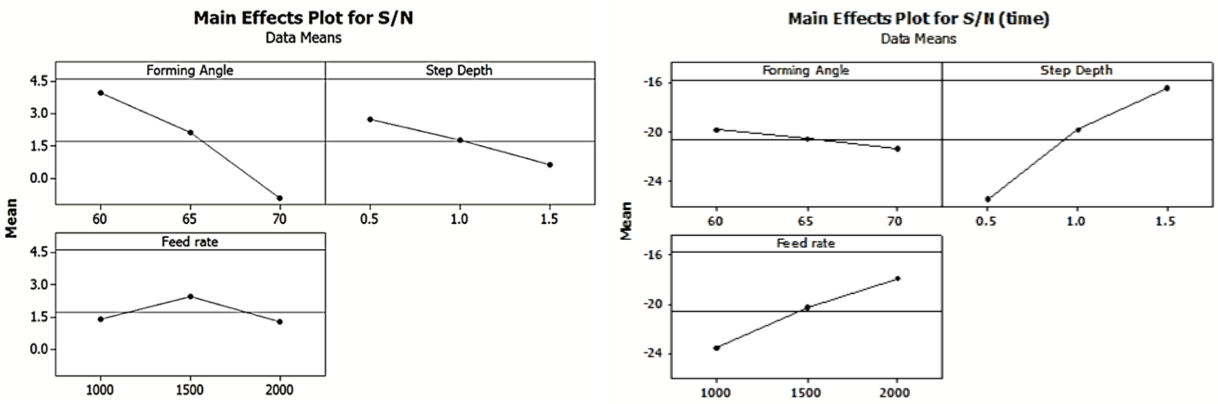


Figure 4. Response graph for surface roughness and forming time

Table 3 shows all roughness values measured. Forming time has been measured during forming operation which is shown in Table 2. From this table, it can be observed that forming time is more for the first experiment with less step depth and lower wall angle. S/N ratio has been calculated using Eq.(4) shown above and means of all 4 roughness values shown in Table were calculated to get the approximate roughness value. The variables affecting surface roughness can be determined by the ANOVA technique. A cut-off criterion is used to categorize the significant factors from insignificant factors. Here in ANOVA F-test has been used as a cut-off criterion. Table 4 shows the S/N ratios for surface roughness and forming time.

Table 3.Experimental results (surface roughness).

Sl. No	A	B	C	R1(μm)	R2(μm)	R3(μm)	R4(μm)	S/N ratio	Mean
1	1	1	1	0.545	0.544	0.476	0.593	5.334341	0.5395
2	1	2	2	0.543	0.502	0.507	0.656	5.106611	0.552
3	1	3	3	0.889	0.814	0.938	0.733	1.441705	0.8435
4	2	1	2	0.501	0.492	1.06	0.662	2.892674	0.67875
5	2	2	3	0.656	0.669	0.834	0.851	2.407754	0.7525
6	2	3	1	0.888	1.37	0.407	0.549	1.061697	0.8035
7	3	1	3	1.07	1.54	0.434	0.533	0.012019	0.89425
8	3	2	1	0.715	1.48	1.66	1.07	-2.17624	1.23125
9	3	3	2	1.28	1.34	0.755	0.770	-0.60407	1.03625

Analysis of experimental results can be done by using the response table and response graph which will investigate the effect of each process parameter on output rank wise. From the response graph, the effect of each level of each parameter on output can be obtained graphically. Response table shows the rank of each parameter on both the responses. S/N and mean response table has been analyzed here. Both these tables and graphs help in summarising the effect of each process parameter on surface roughness as well as forming time. As per the response Table 5, rank of forming an angle, step depth and federate are 1, 2, 3 respectively for surface roughness. Factor ranking is the difference between response extremes. Higher the factor response, higher is the rank. The higher the S/N ratio, the smaller is the variance in the quality of the result. From Response graph A1, B1, C2 are the highest for surface roughness and A1, B3, C3 are highest for forming time in main effect plot.

Optimization of response influenced by input variables is the objective in Response surface methodology (RSM). RSM is a widely used technique to measure surface roughness using mathematical models. Changes are made in input variables in experimental runs to test the response on output. The response can be represented in three-dimensional spaces either as contour plot or as the surface. In this work, surface roughness and forming time are the response and forming an angle, feed rate and step depth are input parameters.

Table 4. ANOVA for surface roughness

	Source	DF	Seq SS	Adj SS	Adj MS	F	P
Surface Roughness	Forming Angle(º)	2	36.499	36.499	18.250	7.84	0.113
	Step depth(mm)	2	6.715	6.715	3.357	1.44	0.409
	Feed Rate(mm/min)	2	2.522	2.522	1.261	0.54	0.649
	Error	2	4.655	4.655	2.327		
	Total	8	50.391				
Forming Time	Source	DF	Seq SS	Adj SS	Adj MS	F	P
	Forming Angle(º)	2	1.775	1.775	0.888	0.26	0.794
	Step depth(mm)	2	239.106	239.106	119.553	34.92	0.028
	Feed Rate(mm/min)	2	83.841	83.841	41.920	12.24	0.076
	Error	2	6.848	6.848	3.424		
	Total	8	331.571				

DF=Degree Of Freedom, SS=Sum of squares, MS=variance (Mean of squares), F=Ratio of two mean square values, P=Determined from F value and degree of freedom

Table 5. Response table.

	Level	Forming Angle	Step Depth	Feed Rate
Surface Roughness	1	3.96089	2.74634	1.40660
	2	2.12071	1.77937	2.46507
	3	-0.922764	0.633111	1.28716
	Factor	4.883654	2.113229	1.17791
	Rank	1	2	3
Forming time	1	-19.8551	-25.4908	-23.5605
	2	-20.5676	-19.8510	-20.3145
	3	-21.4265	-16.5073	-17.9742
	Factor	1.5714	8.9835	5.5863
	Rank	3	1	2

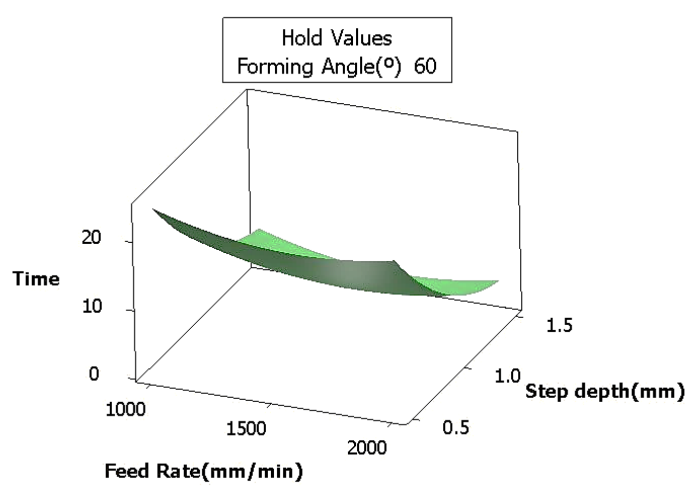
The second order response surface representing surface roughness is given by:

$$\begin{aligned}&10.8390-0.412442\times \mathrm{A}-0.9620\times \mathrm{B}+0.003146\times \mathrm{C}+0.00418\times \mathrm{A}^2\\&+0.152\times \mathrm{B}+4.060\times 10^{-7}\times \mathrm{C}^2+0.010466\times \mathrm{A}\times \mathrm{B}-6.7166\times 10^{-5}\times \mathrm{A}\times \mathrm{C}\end{aligned} \quad (6)$$

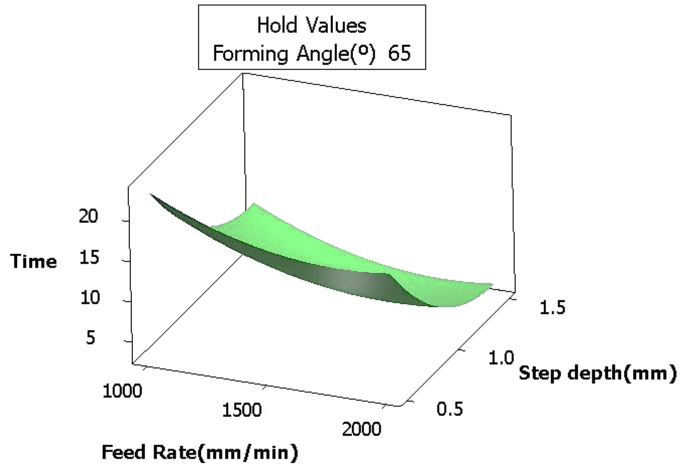
Similarly, from the response graph and table, it was observed that wall angle has less effect on forming time as compared to the other two parameters. So keeping wall angle constant, RSM has been plotted as shown in Figure 5.

The second order response surface representing forming time is given by:

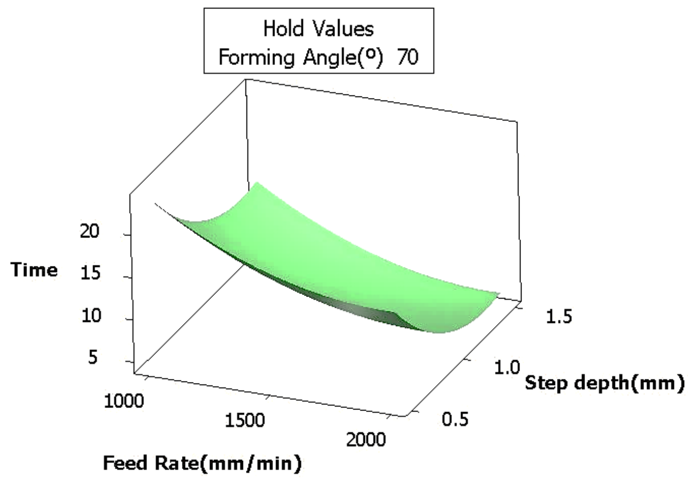
$$\begin{aligned}&210.010-4.68567\times A-94.0067\times B+0.0106433\times C+0.0376667\times A^2\\&+14.2667\times B^2+9.23\times 10^{-6}\times C^2+0.7933\times A\times B-6.7\times 10^{-4}\times A\times C\end{aligned} \quad (7)$$



(a)



(b)



(c)

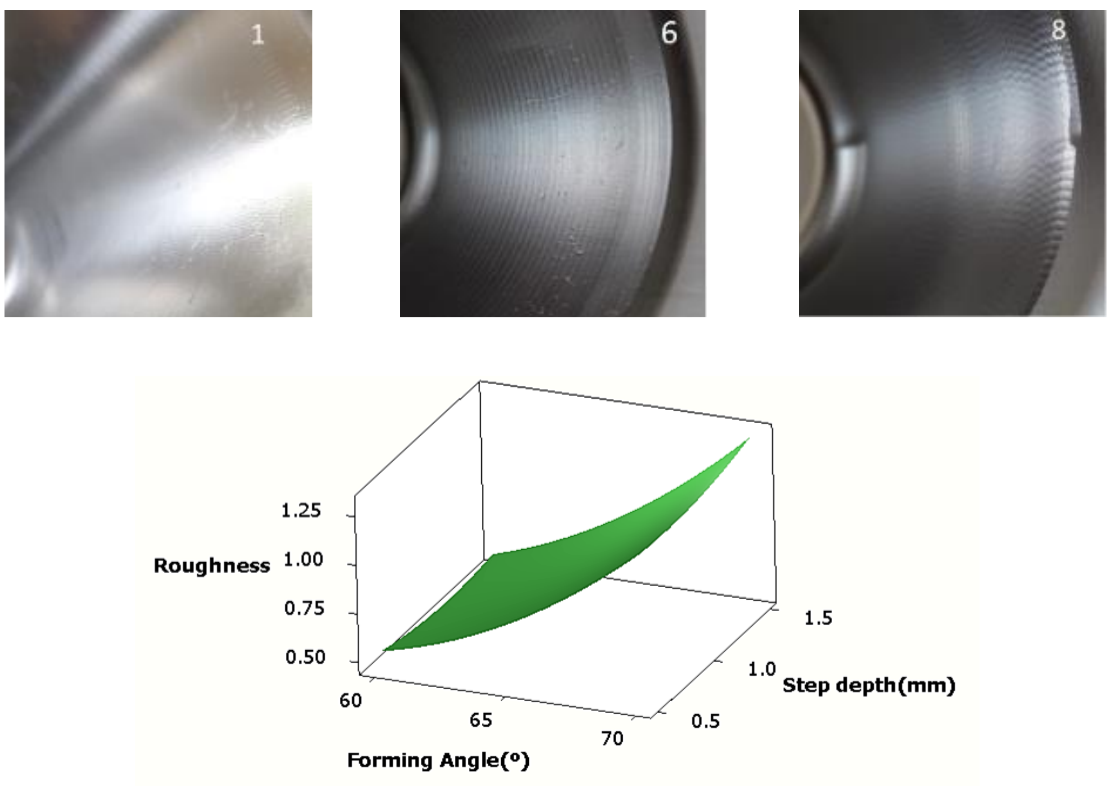
Figure 5. Response surface plot for forming time at constant wall angle (a) Experiment 1,2,3, (b) Experiment 4,5,6 and (c) Experiment 7,8,9.

RESULTS AND DISCUSSION

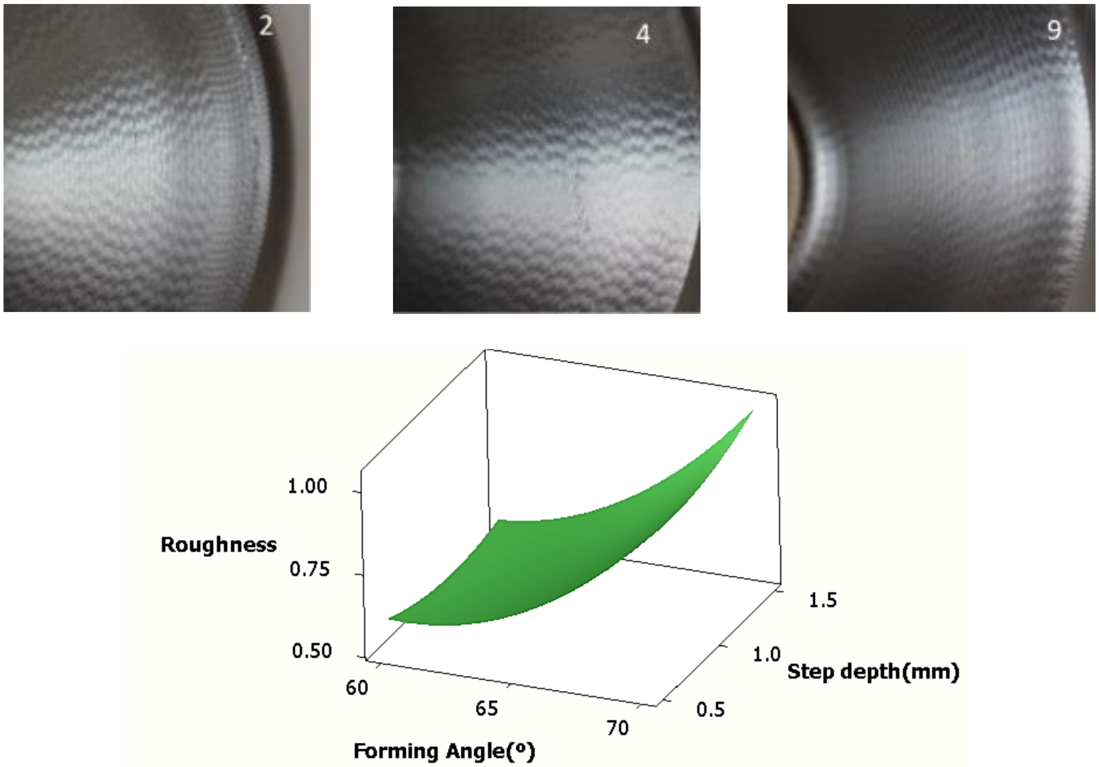
Using L9 orthogonal array combinations 9 experiments have been performed. In Figure 6, the texture of all the formed cups has been shown from Table 4. It can be observed that F statistics are higher for forming an angle. So, feed rate has a negligible effect on roughness as compared to step depth and forming an angle. Similarly, ANOVA Table 4 for time reflects when F statistics is larger than P values small producing a statically significant result. Forming angle has a negligible impact on forming time as compared to other parameters and P value < 0.05 shows step depth has a significant effect on forming time. As per the response Table 5, rank of forming an angle, step depth and federate are 1, 2, 3 respectively for surface roughness. Form Table 5, a ranking of forming an angle, step depth and federate are 3, 1, 2 respectively. Factor ranking is the difference between response extremes. Higher the factor response, higher is the rank. The higher the S/N ratio, the smaller is the variance in the quality of the result. In the main effect plot A_1, B_1, C_2 are the highest for surface roughness and A_1, B_3, C_3 are highest for forming time.

From the Response table and ANOVA test, it can be concluded that surface roughness is affected by forming angle the most and then step depth. Feed rate has the least impact on surface quality. Similarly, from the response table for S/N ration of forming time, it is observed that step depth affects forming the time the most out of all the three parameters. Forming angle has the least effect on forming time. From the response table and graph, it was observed that feed rate has less effect on forming an angle as compared to the other two parameters. So keeping feed rate constant, the response surface has been plotted and compared with experimental result in Figure 6.

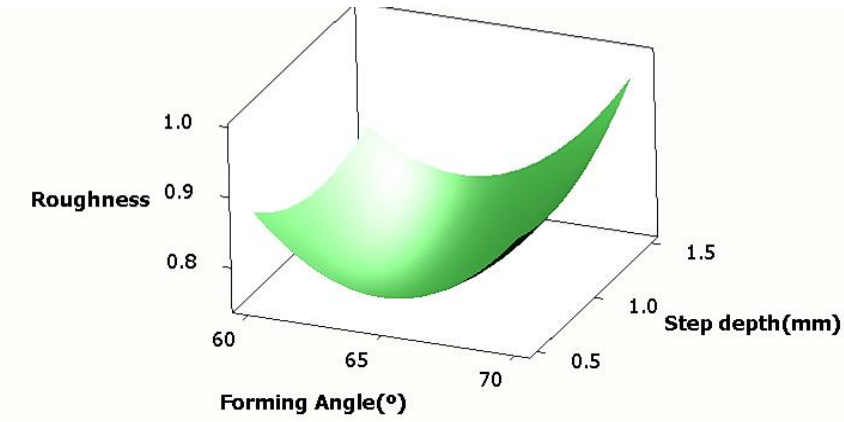
In Figure 6, it can be observed that, at a constant feed rate, surface roughness increases with an increase in feed rate and with an increase in step depth. In photo-1, 6, 8 also, the surface texture changed and seems to be more jagged in Photo-6 due to high step depth. In high step depth, scallop height increases leaving visible unreformed lines on the part. But in 2nd RSM plot, it can be observed that at a constant feed rate of 1500mm/min, the surface roughness is nearly equal in photo-2,4 and rougher in Photo-9 due to higher step depth. In 3rd RSM plot, Surface quality in photo-3 is inferior to the other two.



(a)


2
4
9
Roughness
1.00
0.75
0.50
60
65
70
Forming Angle(°)
0.5
1.0
1.5
Step depth(mm)

(b)



(c)

Figure 6. The texture of the formed sheet and RSM plot at feed rate (a) 1000 mm/min, (b) 1500 mm/min and (c) 2000 mm/min.
(Pictures are labeled as per L9 orthogonal array sequence number)

Table 6. Optimum parameters.

	Parameters	**Forming Angle(°)**	**Step depth(mm)**	**Feed Rate(mm/min)**	**T1 (µm)**	**T2 (µm)**	**T3 (µm)**	**T4 (µm)**
Surface Roughness	Levels	1	1	2	0.108	0.0726	0.177	0.0748
	Values	60	0.5	1500				
Forming Time	Levels	1	3	3	4.54			
	Values	60	1.5	2000				

So in all the experiments, it is observed that higher step depth increases surface roughness due to increase in scallop height. Out of all the experiments, in experiment number-1 surface quality and texture of the surface has better visibility than others. But the time taken in experiment-1 is more than other experiments which are shown in Table 2. Confirmation test has been conducted to confirm the quality of surface roughness and forming time. Using optimum parameters from the response graph shown in Table 6, the experiment has been conducted for forming time and time taken for forming was 4.54min. Also, Roughness was measured using above forming parameters and roughness value is shown in Table 6. Mean of all four readings taken is 0.1081µm. Texture of the final formed cup was found to be smoother and surface quality was improved.

Different materials have been used in ISF for investigating surface roughness by varying various process parameters in literature. As spindle speed has less effect on surface roughness, this parameter from literature has been ignored and the effect of other process parameters on surface roughness has been plotted in Figure 7. There was only limited literature available for investigating surface roughness variation due to wall angle change. Surface roughness variation due to wall angle in Figure 7 (a) shows the opposite trend for two materials. For AA5052 surface roughness decreases with an increase in wall angle, but for Al1100, surface roughness increases with an increase in wall angle. Figure 7 (b) shows the surface roughness deviation due to the change in the tool feed rate for different materials. For almost all the materials, the roughness trend is similar. Surface roughness increases with increase in tool feed rate. Only Al7075 shows a decreasing trend after 5000mm/min feed rate. Figure 7 (c) shows the roughness trend for different materials when step depth varies. At lower step depth, nearly all the materials show lower surface roughness but at higher step depth, drastic variation in roughness has been observed.

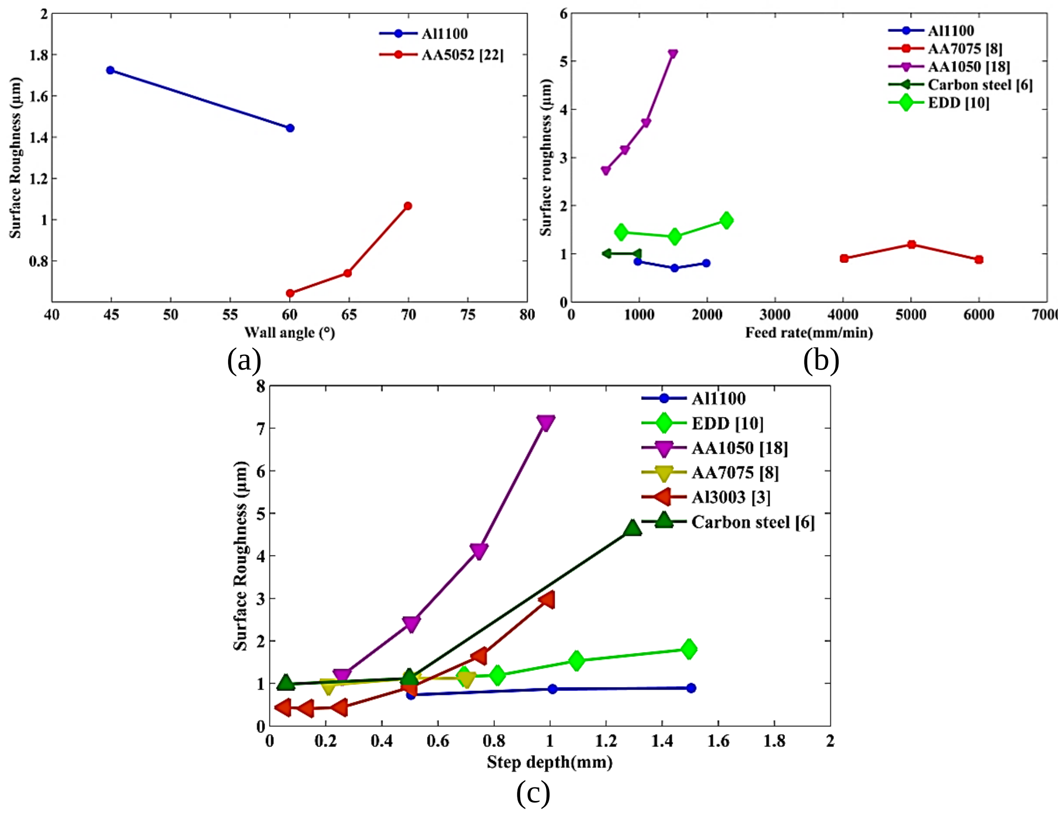


Figure 7. Effect of (a) wall thickness, (b) feed rate and (c) step depth on surface roughness

CONCLUSIONS

The study could successfully identify this parametric influence as well as the optimum parametric setting. It was found that surface roughness can be decreased by reducing the forming angle and step depth. Increase in step depth increases scallop height which leaves unreformed lines on the part. The feed rate has a negligible effect on surface roughness and hence it may be kept constant. Step depth has more effect on forming time than the other two parameters. With an increase in step depth, the forming time decreases but surface roughness increases. Forming angle has very less effect on forming time. With an increase in feed rate, forming time decreases. Step depth is a significant parameter which affects both surface quality and forming time.

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