ISSN: 0974-5823 Vol. 7 No. 1 January, 2022

*International Journal of Mechanical Engineering*

# Process Parameters Optimization in Single Point Incremental Forming Of Al1050

Dina Al-Badri[1], Ahmed Z. M. Shammari[1], Nazar Al-Kharkhi[1]
[1]Department of Automated Manufacturing Engineering, University of Baghdad, Baghdad, Iraq

***Abstract:*****This work aims to optimize surface roughness, wall angle deviation, and average wall thickness as output responses of ALuminium-1050 alloy cone formed by the single point incremental sheet metal forming process. The experiments are accomplished based on the use of a mixed level Taguchi experimental design with an L18 orthogonal array. Six levels of step depth, three levels of tool diameter, feed rate, and tool rotational speed have been considered as input process parameters. The analyses of variance (ANOVA) have been used to investigate the significance of parameters and the effect of their levels for minimum surface roughness, minimum wall angle deviation, and maximum average wall thickness. The results indicate that step depth and tool rotational speed are the most significant parameters on the output responses. The predicted optimal values for the surface roughness, average wall thickness, and wall angle deviation are found to be 0.6363 µm, 0.9442 mm, and 0.0994° respectively. The results have been validated by the confirmation of the experiments and found to be 0.57, 0.9162, and 0.124, respectively, which are within the range of these values.**

***Keywords:*** Single Point Incremental Forming, Taguchi, optimization, ANOVA, AL1050

## 1. INTRODUCTION

The importance of sheet metal forming of aluminum alloys has risen dramatically in the automotive, aircraft, and aerospace industries due to its low density, good strength, and also its corrosion resistance. However, formability is a very important property in sheet metal forming, and the main disadvantage of aluminum alloys is their poor formability compared to steel in conventional forming processes [1].Moreover, dies and punches are used in traditional sheet metal forming operations, which have a high cost associated with a large number of products [2, 3]. Incremental sheet forming (ISF) is created to fulfill the growing need for sheet metal forming while also being a more cost-effective approach.In addition, because of the small plastic zone and incremental nature of the process, SPIF has a better formability than traditional processes, making it simpler to deform sheet metal with limited formability like aluminum alloys [4].Although several studies on the process parameters optimization have been performed in SPIF of aluminum alloys, it is still a challenging task to select and optimize the forming process parameters for good surface quality and accuracy.

Liu et al [5]proposed modeling and optimization of surface roughness for AA7075-O sheets in incremental sheet forming process. The response surface methodology was used to study the effect of four parameters (step down, feed rate, sheet thickness, and tool diameter) on surface finish. From the experimental results with RSM analysis it is showed that most important forming variable on the overall surface finish is thickness, followed by step down. Feed rate and tool diameter, on the other hand, have little effect on overall surface roughness.Gulati et al[6]optimized the wall angle as a measure for the formability and surface roughness as surface quality of Aluminium-6063 alloy formed by the single-point incremental forming process. Taguchi’s L18 orthogonal array were selected to analysis six different parameters as input such as tool radius, sheet thickness, step Size, tool rotational speed, feed rate and lubrication. The results showed that surface roughness decreases as feed rate, sheet thickness, step size, and tool rotating speed are reduced, and increases as tool radius is increased. Also, thefindings showed that the formability increases with the decrement of tool radius, feed rate and step size and with the increase of tool rotational speed and sheet thickness.Baruah et al[7] tried to improve formability and reduce surface roughness in Incremental Sheet Metal Forming (ISF) process for AA5052-H32. Taguchi’s orthogonal L9 array with grey relational analysis and ANOVA was used todetermine optimum parameters namely vertical step-down, feed rate, spindle speed, and lubrication for maximizing the formability and minimizing the Roughness. The results identified that lubrication is the highest affecting factor for followed by vertical step down and speed while the least effect is for feed rate.

Pandivelan et al[8]studied the effect of tool speed rotation, vertical step down, and tool diameter on the formability of AA 5052 sheets in terms of wall angle. They tried to optimize the process parameters for maximum formability at maximum wall angle using Taguchi s L9 orthogonal array design of experiments. The tool diameter is recognized as the significant factor for higher formability, followed by vertical step down and speed.

Kumar et al[9]investigated the effects of tool diameter, step size, and spindle speed on surface roughness of AA2024-O sheets using SPIF process. Experimental work results showed that roughness of the formed components increases with the decrease in tool diameter and spindle speed whereas decreases with the decrease in step size.

Kumar et al [10]studied the effect of tool shape, tool diameter, wall angle, step size, sheet thickness, and tool rotation as input process parameters on the formability of AA2024-O aluminum alloy in single point incremental forming process. Formability is found to improve when tool diameter, spindle speed, and sheet thickness increased. The formability is reduced when the wall angle and step size increased.Ismail et al[2] investigated the impact of step size, robot speed, and wall angle on the average surface roughness of AA3003 aluminum alloy sheet in a robot-based SPIF process to achieve excellent surface quality. The step size is discovered to be the most significant factor followed by the robot speed and wall angle is highly insignificant as a result of experimental trials using Taguchi orthogonal array and ANOVA.Mohanty et al [11]Tried to optimize forming time and surface roughness influenced by input variables like step depth, feed rate and wall angle in single point incremental sheet metal forming ofAl-1100. The Taguchi L9 orthogonal array with the response surface method was used for minimizing the surface roughness and forming time. It was found that surface roughness can be decrease by reducing the forming angle and step depth while forming time decrease with the increase of step depth and feed rate.

In single point incremental forming, the process parameters impacting profile errors and surface roughness were investigated (SPIF) by Dabwan et al [12]. The experimental study was designed utilizing a full factorial design with four process parameters: tool diameter (d), step depth (s), sheet thickness (t), and feed rate (f). The data were analyzed using techniques such as analysis of variance, regression, and optimization. In terms of lowering roughness, waviness, circularity, and side angle errors, smaller t, greater d, and smaller s give improved profile accuracy and surface quality.

In incremental sheet metal forming, the literature contains just very few researches on the aluminum Al-1050. There has never been a study of the influence of a combination of four process parameters, namely step depth (z), tool diameter (d), feed rated (f), and spindle speed (s) on obtaining good surface quality, formability and acceptable accuracy, to the best of the authors' knowledge. The purpose of this study is to investigate these parameters on surface roughness, average wall thickness, and wall angle deviation in SPIF. The experiment is set up with the L18 orthogonal array Taguchi mixed design approach. Techniques including analysis of variance, Confidence Interval around the Estimated Mean, and optimization are used toanalyze the data.

## 2. EXPERIMENTAL WORK

### 1.1Experimental setup

Forming operations were conducted on C-tek three-axis (KM-80D) CNC milling machine shown in Figure 1. Forming frame was designed and built to fix the blank sheet on the CNC milling machine table (Figure 2). The geometry of part is a conical shape with dimensions of 130 mm upper diameter, 40 mm in height and a wall angle of 40 degree and the CAD-model profile to be formed was generated in SOLIDWORKS as shown in Figure 3. HSMWorks software was used to create the spiral tool path that was used to manufacture the sheet (Figure 4). A transition step approach was used to build and link tool contours [13]. The studied process parameters i.e. step depth, tool diameter, feed rate, and tool seed (z, d, f, and s) are shown in Figure 5. Three spherical tip forming HSS tools of diameters 8 mm, 10 mm, and 12 mm were designed and manufactured for the deformation of the sheets, as shown in Figure 6. Eighteen sheet blanks of aluminum (Al 1050) with dimension (225 x 225 x 1 mm) were used to perform the experiments. The chemical composition and mechanical properties of this Aluminum (Al 1050) are illustrated in Table 2 and Table 3.


Fig.1. experimental setup

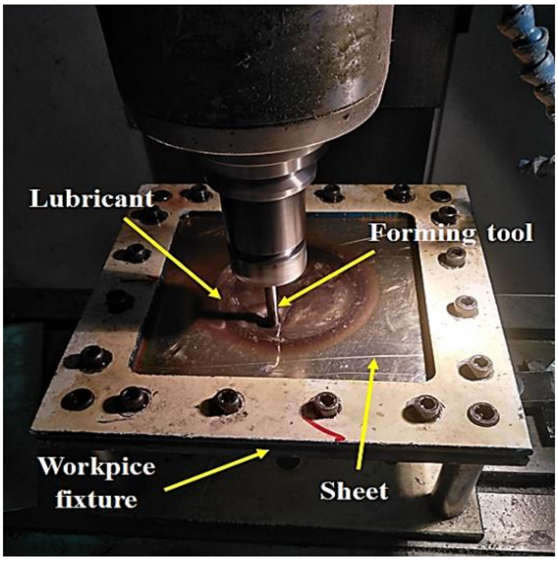

Fig.2. Forming frame

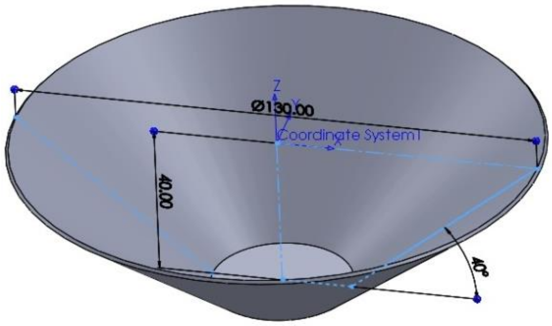

Fig.3. CAD model

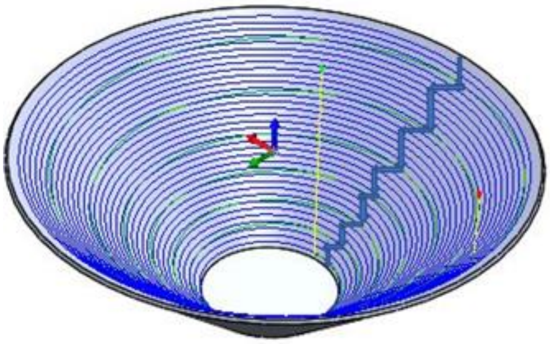
Fig.4. Tool path

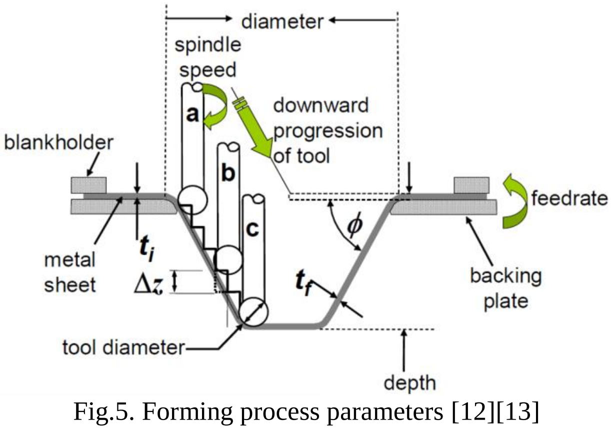

Fig.5. Forming process parameters [12][13]

Fig.6. Forming tools

Table 1. Composition of AL1050

| Material | Measured | ASTM Standard |
|---|---|---|
| AL% | 99.5 | ≤99.6 |
| Si% | 0.142 | ≤0.25 |
| Fe% | 0.315 | ≤0.4 |
| Cu% | 0.013 | ≤0.05 |
| Mn% | 0.013 | ≤0.05 |
| Mg% | 0.001 | ≤0.05 |
| Cr% | 0.001 | ≤0.03 |
| Ni% | 0.003 | ≤0.03 |
| Zn% | 0.006 | ≤0.05 |

Table 2. Mechanical properties of AL1050

| Material | Measured | ASTM Standard |
|---|---|---|
| Yield Stress (MPa) | 71 | 65-78 |
| Tensile Strength (MPa) | 86 | 80-100 |
| Modulus of Elasticity (GPa) | 72 | 70-75 |
| Elongation % | 4.5 | 3.5-4.2 |
| Poisson's Ratio | 0.33 | 0.33 |

**1.2Surface roughness measurement**

Surface roughness is a critical parameter that is related to the surface quality of industrial products. The motion of the forming tool on the sheet in the incremental metal forming process leads to surface roughness on the work sheet. Surface roughness measurements were made with time group TR-220 surface roughness tester (Figure7). The average roughness (Ra) was assessed in this study, because it is widely used as a metric of surface roughness. For all the measurements, the cutoff length was taken as 0.8mm and the evaluation length was taken as 4 mm. The measurement process was implemented by taking an average value of Ra for three different positions.


Fig.7. Surface roughness measurement

**1.3 Average Wall Thickness Measurement**

In the manufacturing industry, the rate of thickness decrease caused by plastic deformation of work piece due to the tool movement relative to the sheet is of considerable importance, and it is one of the fundamental defects of incremental forming [14]. The wall thickness measurement was performed by using a micrometer with accuracy of 0.01, as shown in Figure8.The procedure was carried out by averaging the wall thickness values measured at six distinct places.

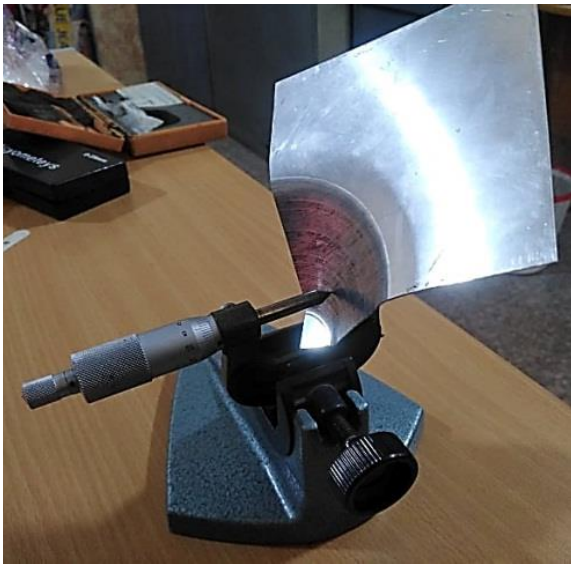

Fig. 8. Wall average thickness measurement

**1.4 Wall angle deviation measurement**

The wall angle is the angle formed by the horizontal XY-plane and the side walls of the conical profile (Fig. 5). The absolute value of the difference between the actual and the CAD side angles (40°) was used to compute the wall angle deviation or inaccuracy. Figure9 shows the setup for the coordinates measuring process using the CMM with touch prob.

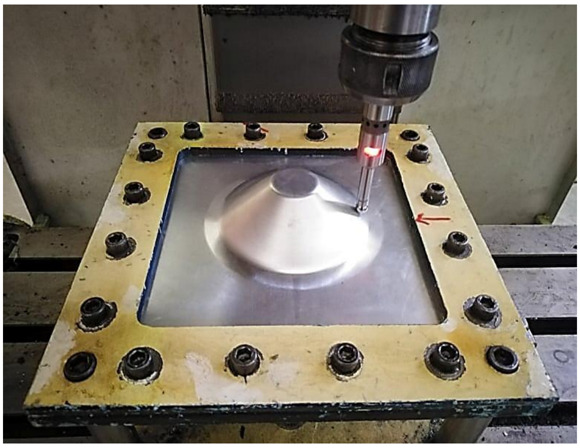

Fig. 9. Wall angle deviation measurement

## 3. RESULTS AND DISCUSSIONS

The objective of this work is to analyze the effect of the process parameters like step depth, tool diameter, feed rate, and spindle speed on the output response namely, surface roughness, average wall thickness, and wall angle deviation of incremental sheet metal forming of AL1050 sheet. The main effects of process parameters were plotted and the response curves (main effects) are used for examining the parametric effects on the response characteristics. To identify the significant parameters and quantify their influence on the response characteristics, data analysis of variance (ANOVA) was used. Analyzing the response curves and ANOVA tables yielded the most favorable values (optimal settings) of process variables in terms of mean response characteristics. On a confirmation test, the 95 % confidence interval (CI) for the predicted mean of optimum responses was calculated.Taguchi L18 mixed level design was used to conduct the experimental plan. As given in Table 4, six levels of step depth (z) and three levels of each tool diameter (d), feed rate (f), and spindle speed (s) were selected as the input parameters. In total, 18 experiments were carried out based on Taguchi mixed level design for the four factors (i.e. six levels for the first factor and three level for the other three factors), as presented in Table 3. The photographs of the formed sheets based on this experimental plan are shown in Figure10. Experimental plan are given in Table 4and results are shown in Table 5 and Table 6 for Surface roughness (Ra), Average wall thickness (Th), and Wall angle deviation (Δθ) as the process outputs responses.

Table 3. Forming parameters and their levels

| Input Parameters | Units | Coded Levels | Actual Values |
|---|---|---|---|

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Step depth (z) | mm | 1 | 2 | 3 | 4 | 5 | 6 | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 |
| Tool diameter (d) | mm | 1 | 2 | 3 | | | | 8 | 10 | 12 | | | |
| Feed rate (f) | mm/min | 1 | 2 | 3 | | | | 500 | 1500 | 2500 | | | |
| Spindle speed (s) | rpm | 1 | 2 | 3 | | | | 2000 | 4000 | 6000 | | | |

Fig. 10. Photographs of formed sheets

Table 4. Taguchi mixed level design for input parameters

| *Run Order* | z | | d | | f | | s | |
|---|---|---|---|---|---|---|---|---|
| | *Coded* | *Actual* | *Coded* | *Actual* | *Coded* | *Actual* | *Coded* | *Actual* |
| 1 | 1 | 0.1 | 1 | 8 | 1 | 500 | 1 | 2000 |
| 2 | 1 | 0.1 | 2 | 10 | 2 | 1500 | 2 | 4000 |
| 3 | 1 | 0.1 | 3 | 12 | 3 | 2500 | 3 | 6000 |
| 4 | 2 | 0.3 | 1 | 8 | 1 | 500 | 2 | 4000 |
| 5 | 2 | 0.3 | 2 | 10 | 2 | 1500 | 3 | 6000 |
| 6 | 2 | 0.3 | 3 | 12 | 3 | 2500 | 1 | 2000 |
| 7 | 3 | 0.5 | 1 | 8 | 2 | 1500 | 1 | 2000 |
| 8 | 3 | 0.5 | 2 | 10 | 3 | 2500 | 2 | 4000 |
| 9 | 3 | 0.5 | 3 | 12 | 1 | 500 | 3 | 6000 |
| 10 | 4 | 0.7 | 1 | 8 | 3 | 2500 | 3 | 6000 |
| 11 | 4 | 0.7 | 2 | 10 | 1 | 500 | 1 | 2000 |
| 12 | 4 | 0.7 | 3 | 12 | 2 | 1500 | 2 | 4000 |
| 13 | 5 | 0.9 | 1 | 8 | 2 | 1500 | 3 | 6000 |
| 14 | 5 | 0.9 | 2 | 10 | 3 | 2500 | 1 | 2000 |
| 15 | 5 | 0.9 | 3 | 12 | 1 | 500 | 2 | 4000 |
| 16 | 6 | 1.1 | 1 | 8 | 3 | 2500 | 2 | 4000 |
| 17 | 6 | 1.1 | 2 | 10 | 1 | 500 | 3 | 6000 |
| 18 | 6 | 1.1 | 3 | 12 | 2 | 1500 | 1 | 2000 |

Table 5. Measured responses obtained after experiments

| Exp. No. | Surface Roughness (µm) | | | Average Wall Thickness (mm) | | | | | | Wall Angle Deviation (°) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ra1 | Ra2 | Ra3 | Th1 | Th2 | Th3 | Th4 | Th5 | Th6 | θ1 | θ2 | θ3 | θ |
| 1 | 0.85 | 0.49 | 0.63 | 0.86 | 0.87 | 0.85 | 0.78 | 0.83 | 1.03 | 40.065 | 40.167 | 39.952 | 40.261 |
| 2 | 1.12 | 1.11 | 1.23 | 0.89 | 0.88 | 0.85 | 0.87 | 0.78 | 1.05 | 39.703 | 39.502 | 39.920 | 39.808 |
| 3 | 0.85 | 0.75 | 0.79 | 0.91 | 0.86 | 0.89 | 0.88 | 0.87 | 1.04 | 40.393 | 40.298 | 39.898 | 40.126 |
| 4 | 1.31 | 0.94 | 1.05 | 0.98 | 0.91 | 0.88 | 0.82 | 0.8 | 1.0 | 40.218 | 40.374 | 40.283 | 40.212 |
| 5 | 1.56 | 1.63 | 1.61 | 0.99 | 0.97 | 0.88 | 0.85 | 0.87 | 1.04 | 40.381 | 40.234 | 40.142 | 40.427 |
| 6 | 0.66 | 0.82 | 0.96 | 0.87 | 0.81 | 0.83 | 0.82 | 0.81 | 1.01 | 39.548 | 39.695 | 39.327 | 39.523 |
| 7 | 1.87 | 1.69 | 1.46 | 0.91 | 0.85 | 0.88 | 0.85 | 0.83 | 1.04 | 39.958 | 38.879 | 40.472 | 39.677 |
| 8 | 1.5 | 1.56 | 1.42 | 0.96 | 0.95 | 0.89 | 0.84 | 0.86 | 1.01 | 39.927 | 40.054 | 39.538 | 39.764 |
| 9 | 2.1 | 2.51 | 1.02 | 0.99 | 0.96 | 0.85 | 0.87 | 0.84 | 1.03 | 40.512 | 39.634 | 40.230 | 40.165 |
| 10 | 2.03 | 1.79 | 1.92 | 1.1 | 0.97 | 0.89 | 0.89 | 0.95 | 1.03 | 39.841 | 39.276 | 40.385 | 39.814 |
| 11 | 1.46 | 1.84 | 1.34 | 1.11 | 0.91 | 0.85 | 0.86 | 0.63 | 1.02 | 39.576 | 38.732 | 40.121 | 39.576 |
| 12 | 1.35 | 1.39 | 1.44 | 1.00 | 0.81 | 0.90 | 0.83 | 0.87 | 1.00 | 39.484 | 40.541 | 38.594 | 39.740 |
| 13 | 2.01 | 2.83 | 2.34 | 1.12 | 0.65 | 0.96 | 0.91 | 0.87 | 1.03 | 39.846 | 39.414 | 40.192 | 39.807 |
| 14 | 1.94 | 1.87 | 1.75 | 0.56 | 0.98 | 0.87 | 0.89 | 0.58 | 1.01 | 39.784 | 40.783 | 40.824 | 40.464 |
| 15 | 1.83 | 2.10 | 2.41 | 0.96 | 0.51 | 0.96 | 0.94 | 0.91 | 1.01 | 40.023 | 40.523 | 40.714 | 40.296 |
| 16 | 2.32 | 2.88 | 3.12 | 0.91 | 0.5 | 1.1 | 1.00 | 0.79 | 1.00 | 40.545 | 39.857 | 40.714 | 40.372 |
| 17 | 2.6 | 2.55 | 2.7 | 1.1 | 0.84 | 0.58 | 0.92 | 0.93 | 1.03 | 40.234 | 40.512 | 39.741 | 40.216 |
| 18 | 1.79 | 2.26 | 1.87 | 0.74 | 1.01 | 0.87 | 0.83 | 0.54 | 1.02 | 39.857 | 38.645 | 39.743 | 39.495 |

Table 6. Average Results of Responses

| *Run Order* | z | d | f | s | Surface Roughness (Ra) (µm) | Average Wall Thickness (Th) (mm) | Wall Angle Deviation (Δθ) (°) |
|---|---|---|---|---|---|---|---|
| 1 | 0.1 | 8 | 500 | 2000 | 0.657 | 0.870 | 0.261 |
| 2 | 0.1 | 10 | 1500 | 4000 | 1.153 | 0.896 | 0.192 |
| 3 | 0.1 | 12 | 2500 | 6000 | 0.797 | 0.958 | 0.126 |
| 4 | 0.3 | 8 | 500 | 4000 | 1.100 | 0.898 | 0.212 |
| 5 | 0.3 | 10 | 1500 | 6000 | 1.600 | 0.933 | 0.252 |
| 6 | 0.3 | 12 | 2500 | 2000 | 0.813 | 0.886 | 0.427 |
| 7 | 0.5 | 8 | 1500 | 2000 | 1.673 | 0.879 | 0.323 |
| 8 | 0.5 | 10 | 2500 | 4000 | 1.493 | 0.918 | 0.236 |
| 9 | 0.5 | 12 | 500 | 6000 | 1.877 | 0.928 | 0.165 |
| 10 | 0.7 | 8 | 2500 | 6000 | 1.913 | 0.923 | 0.186 |
| 11 | 0.7 | 10 | 500 | 2000 | 1.547 | 0.857 | 0.424 |
| 12 | 0.7 | 12 | 1500 | 4000 | 1.393 | 0.892 | 0.260 |
| 13 | 0.9 | 8 | 1500 | 6000 | 2.393 | 0.923 | 0.193 |
| 14 | 0.9 | 10 | 2500 | 2000 | 1.853 | 0.835 | 0.464 |
| 15 | 0.9 | 12 | 500 | 4000 | 2.113 | 0.882 | 0.296 |
| 16 | 1.1 | 8 | 2500 | 4000 | 2.773 | 0.853 | 0.372 |
| 17 | 1.1 | 10 | 500 | 6000 | 2.617 | 0.901 | 0.216 |
| 18 | 1.1 | 12 | 1500 | 2000 | 1.973 | 0.815 | 0.495 |
| Average | | | | | 1.6521 | 0.8915 | 0.2833 |

### 3.1 Analysis of Variance (ANOVA) for Responses

The statistical analysis of variance ANOVA hasbeen used to analyze the results for identifying the significant process parameters affecting on the all responses (Ra, Th, and Δθ) and are given in Table 7, 8 and 9. The ANOVA for the responses at least 0.05 significance level or 95% confidence interval was carried thus, the parameters to be significant must have P-value less than or equal to 0.05[2].As is obvious from the Table (7), the effect of step depth is found to be highly significant on Ra with contribution of 78.75% followed by tool speed. Theeffect of tool diameter and feedrate are found insignificant with P-value more than 0.05.For the average wall thickness measure (Th), Table 8 shows that the effect of tool speed and step depth are made known to have significant outcomes with contributions of 69.58% and 29.58%, respectively but tool speed and feed rate are found with insignificant effect on Th.Table 9 shows the considerable significant terms on the wall angle deviation. The tool speed followed by step depth is significantly affected on Δθ with contributions of 68.41% and 26.24%, respectively, but the tool diameter and feed rate are not significant.

Table 7. Analysis of variance for means for surface roughness

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | % C |
|---|---|---|---|---|---|---|---|
| Step depth | 5 | 5.72014 | 5.72014 | 1.144030 | 55.52 | 0.000 | 78.75 |
| Tool Diameter | 2 | 0.12876 | 0.12876 | 0.064380 | 3.12 | 0.118 | 1.77 |
| Feed rate | 2 | 0.01716 | 0.01716 | 0.008580 | 0.42 | 0.677 | 0.24 |
| Tool speed | 2 | 1.39778 | 1.39778 | 0.698890 | 33.92 | 0.001 | 19.24 |
| Residual Error | 6 | 0.12362 | 0.12362 | 0.020600 | | | |
| Total | 17 | 7.38747 | 7.38747 | | | | |
| Model Summary | S 0.1435 | R-Sq 98.33% | R-Sq(adj) 95.26% | | | | |

Table 8. Analysis of variance for means for average wall thickness

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | %C |
|---|---|---|---|---|---|---|---|
| Step depth | 5 | 0.006378 | 0.006378 | 0.001276 | 6.35 | 0.022 | 29.58 |
| Tool diameter | 2 | 0.000039 | 0.000039 | 0.000019 | 0.10 | 0.909 | 0.18 |
| Feed rate | 2 | 0.000144 | 0.000144 | 0.000072 | 0.36 | 0.712 | 0.67 |
| Tool speed | 2 | 0.015006 | 0.015006 | 0.007503 | 37.36 | 0.000 | 69.58 |
| Residual Error | 6 | 0.001205 | 0.001205 | 0.000201 | | | |
| Total | 17 | 0.022773 | | | | | |
| Model Summary | S 0.0142 | R-Sq 94.71% | R-Sq(adj) 85.01% | | | | |

Table 9. Analysis of variance for means for wall angle deviation

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | %C |
|---|---|---|---|---|---|---|---|
| Step depth | 5 | 0.052099 | 0.052099 | 0.010420 | 8.27 | 0.012 | 26.24 |
| Tool diameter | 2 | 0.005871 | 0.005871 | 0.002936 | 2.33 | 0.178 | 2.96 |
| Feed rate | 2 | 0.004737 | 0.004737 | 0.002369 | 1.88 | 0.232 | 2.39 |
| Tool speed | 2 | 0.135817 | 0.135817 | 0.067909 | 53.88 | 0.000 | 68.41 |
| Residual Error | 6 | 0.007562 | 0.007562 | 0.001260 | | | |
| Total | 17 | 0.206086 | | | | | |
| Model Summary | S 0.0355 | R-Sq 96.33% | R-Sq(adj) 89.60% | | | | |

### 3.2 Analysis of Surface Roughness

The means response table and the main effects plot of means for Ra are illustrated in Table 10and Figure11, respectively. As shown in Figure11, Ra increases with increase in step depth and step size has a significant effect on the surface roughness. Increased surface roughness is caused by the fact that with larger step sizes, a greater depth must be deformed in a single run, increasing the forming force and increasing the area involved in the tool sheet interface[6]. Similarly, tool spindle speed (s) increases Ra, increase in tool speed causes an increase in forming temperatures. The formability of aluminum alloy sheets is mostly influenced by temperature. So, large rotating speed result in higher forming temperatures in the contact area between tool and sheet, which softens the material, making the outer surface of aluminum alloy easy to be cut, chip formation and stripped [15].On the contrary to step depth and spindle speed, themain effect of Tool diameter (d) and feed rate has opposite trend. Surface roughness has decreased as d was increased.The main reason behind this is that small tool diameter mean that small contact area between the tool and sheet which resulting in higher cutting forces and a larger mean surface roughness. Thisconfirms with the previous studies on surface roughness [6].

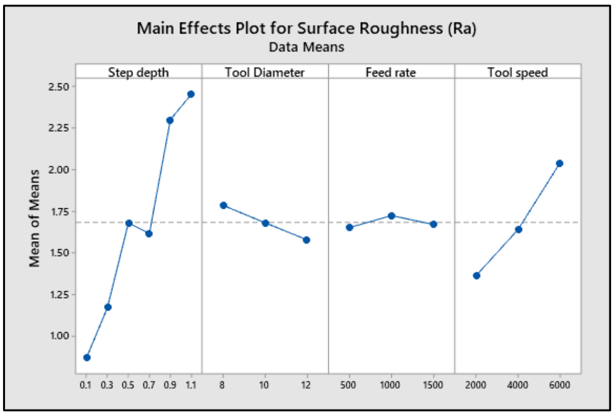

Fig. 11. Main effects plot for Surface Roughness

Moreover, excessive wear during the forming process when using small diameter as compared to the tool with the larger d [12]. The effect of feed rate was very small and agrees with the literatures.

Table 10 shows that the vertical step depth is the most effective process parameter on Ra and it is ranked the first. The tool speed has the second effect on the Ra, followed by tool diameter and feed rate, respectively.

Table10. Response Table for Means for Surface Roughness (Ra)

| Level | Step depth | Tool Diameter | Feed rate | Tool speed |
|---|---|---|---|---|
| 1 | 0.8690 | 1.7865 | 1.6522 | 1.3637 |
| 2 | 1.1710 | 1.6815 | 1.7248 | 1.6412 |
| 3 | 1.6810 | 1.5793 | 1.6703 | 2.0425 |
| 4 | 1.6177 | | | |
| 5 | 2.3017 | | | |
| 6 | 2.4543 | | | |
| Delta | 1.5853 | 0.2072 | 0.0727 | 0.6788 |
| Rank | 1 | 3 | 4 | 2 |

### 3.3 Analysis of Average Wall Thickness

The thickness reduction is one of the main defects of incremental forming [14]. So, maximum average wall thickness of the plate means that less reduction in thickness during incremental forming. The main effect plot of the process parameters on the Average wallthickness (Th) and the mean response table are shown in Figure12 and Table 11, respectively. It is observed that the spindle speed has the more influential impacts on Th than the other process parameters and the average thickness increase with the increase of spindle speed.As mentioned before the increase in the spindle speed increases the friction at tool-sheet contact which results an increase in the local forming temperatures [15]. The increase in forming temperature causes an increase in the ductility of the material leading to increase inthe formability [10, 16].

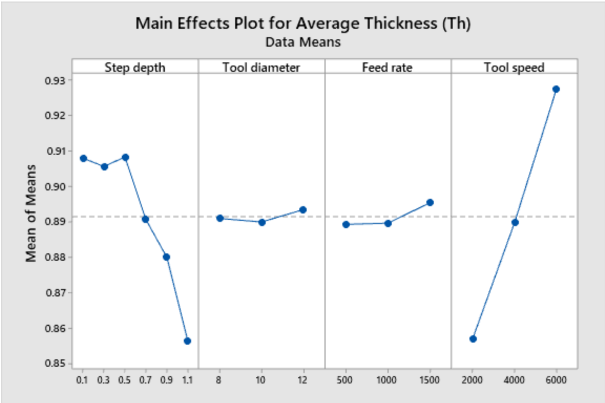

Fig. 12. Main effects plot for Average Thickness

The average wall thickness mostly tends to decrease with increasing step depth.The formability was found to be reduced with the increase of the step size. The reduction in formability refers to less thickness led to fracture and this is in line with the opinion of [17].The tool diameter and feed rate show insignificant effect on average wall thickness and there is a very slight improvement of thickness reduction with the larger tool diameter and higher feed rate, this is agreed with [18].

It can be illustrated from response Table 11 for Th that the tool speed has the highest significant effecton Th followed by step depth, while the tool diameter and the feed rate have insignificant effect.

Table 11. Response Table for Means for average wall thickness (Th)

| Level | Step depth | Tool diameter | Feed rate | Tool speed |
|---|---|---|---|---|
| 1 | 0.9080 | 0.8910 | 0.8893 | 0.8570 |
| 2 | 0.9057 | 0.8900 | 0.8897 | 0.8898 |
| 3 | 0.9083 | 0.8935 | 0.8955 | 0.9277 |
| 4 | 0.8907 | | | |
| 5 | 0.8800 | | | |
| 6 | 0.8563 | | | |
| Delta | 0.0520 | 0.0035 | 0.0062 | 0.0707 |
| Rank | 2 | 4 | 3 | 1 |

### 3.4 Analysis of Wall angle deviation

Figure13 and Table 12show the main effect plot and response table for means for each variable on wall angle deviation (Δθ), respectively. As it is clear from Figure13, the wall angle deviation mostly increases with the increase in a step depth. Generally, as the step size increases, more plastic deformation happen in the formed part led wall angle error increases and this agree with [12].

It is clear from the main effect plot that less wall angle error is achieved with the less tool diameter (8 mm). The forming force decreases by decreasing the tool diameter this cause less spring back and less wall angle deviation or error [19]. The effect of feed rate is not significant on the side angle error as shown in Figure13.

On the contrary to the other parameters the increase in the spindle speed causes significant decrease in the wall angle deviation.This is the same reason as that mentioned for the average thickness in which the increases in the spindle speed leads to increase in forming temperature. The ductility of the material increases with the increases in temperature which improve formability and then reduce spring back led to less wall angle deviation.

Table 12 shows that the tool speed is the most effective process parameter on Δθ and it is ranked the first. The step depth has the second effect on the Δθ, followed by feed rate and tool diameter, respectively.

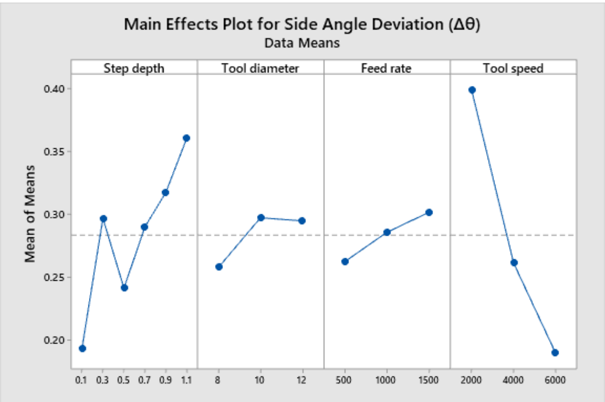


Fig.13. Main effects plot for wallangle deviation

Table 12. Response Table for Means for wall angle deviation (Δθ)

| Level | Step depth | Tool diameter | Feed rate | Tool speed |
|---|---|---|---|---|
| 1 | 0.1930 | 0.2578 | 0.2623 | 0.3990 |
| 2 | 0.2970 | 0.2973 | 0.2858 | 0.2613 |
| 3 | 0.2413 | 0.2948 | 0.3018 | 0.1897 |
| 4 | 0.2900 | | | |
| 5 | 0.3177 | | | |
| 6 | 0.3610 | | | |
| Delta | 0.1680 | 0.0395 | 0.0395 | 0.2093 |
| Rank | 2 | 4 | 3 | 1 |

## 4. OPTIMAL DESIGN

### 4.1 Estimating of Optimum mean and confidence interval

Objective functions of the responses are to minimize each of surface roughness, wall angle deviation, and to maximize average wall thickness. The main effect plot is used to estimate the mean of responses with optimal design conditions [6]. In this experimental analysis, from Figure 11, 12 and 13 and Table 10, 11 and 12 the optimum levels of the input parameters giving minimum Ra, minimum Δθ and maximum Th are achieved in Table 13.Ra is lower when first level of step depth (z1), third level of tool diameter (d3), third level of feed rate (f1) and the first level of tool speed (s1). So, Ra rates at the levels of z1, d3, f1, and s1 are 0.8690, 1.5793, 1.6522, and 1.3637, respectively. Higher Th is achieved when first level of step depth (z3), third level of tool diameter (d3), third level of feed rate (f3) and the third level of tool speed (s3). Average thickness at the levels of z3, d3, f3, and s3 are 0.9083, 0.8935, 0.8955, and 0.9277, respectively.The minimum value of Δθ is at first level of step depth (z1), first level of tool diameter (d1), first level of feed rate (f1) and the third level of tool speed (s3). Side angle error at the levels of z1, d1, f1, and s3 are 0.1930, 0.2578, 0.2623, and 0.1897, respectively.
The mean values of the optimum responses are predicted [20] as in equations (1) −(3):

$$Ra = z1 + d3 + f1 + s1 - 3T = 0.5079\ \mu m \quad (1)$$

$$Th = z3 + d3 + f3 + s3 - 3T = 0.9505\ mm \quad (2)$$

$$\Delta\theta = z1 + d1 + f1 + s3 - 3T = 0.0529° \quad (3)$$

Where T is the average of the related responses from Table 6.
Only the influence of the significant factors is used to predict the optimal mean value of each response characteristic[6]. The insignificant parameters with P > 0.05 (Tables 7 to 9) are eliminated and the mean predicted optimum value of the output responses will be:

$$Ra = z1 + s1 - T = 0.5806\ \ \mu m \quad (4)$$

$$Th = z1 + s3 - T = 0.9445\ mm \quad (5)$$

$$\Delta\theta = z1 + s3 - T = 0.0994° \quad (6)$$

**4.2 Confidence Interval around the Estimated Mean**

Confirmation experiments are an important step in Taguchi's optimization approach for validating the predicted results. Thus a 95% confidence interval (CI) for the predicted mean of optimum responses on a confirmation test is estimated using the Eq. (7) and equation (8)[6] given below:

$$\mathrm{CI} = \sqrt{f_{\propto}(\alpha, 1, f_e)\left(\frac{1}{\eta_{eff}} + \frac{1}{r}\right)V_e} \quad (7)$$

where, $f_{\propto}$ is found from The F Distribution table, $f_e$is degrees of freedom for error, $\eta_{eff}$ = effective number of replications

$$\eta_{eff} = \frac{N}{1 + total\ degree\ of\ freedom} \quad (8)$$

where N = total number of experiments, $V_e$ = error of Adj MS, r = number of repetitions for confirmation experiment, α= risk (0.05), Confidence = $1 - \alpha$
The confidence interval denotes the range of values between which the true average can fall at a given confidence level. Statistically it specifies that the true averages have a chance of being bigger than the estimate of the mean or it have a chance of being less than the estimate of the mean. Then from the above equations the calculated confidence interval of all response are:

(a) For surface roughness (Ra):

$f_e = 6$ (Table 7), $f_{\propto}(0.05, 1, 6) = 5.99$

$$\eta_{eff} = \frac{18}{1 + (5 + 2)} = 2.25$$

$$\mathrm{CI} = \sqrt{5.99\left(\frac{1}{2.25} + \frac{1}{3}\right)0.02060} = 0.3098$$

Thus the confidence interval of the predicted optimal Ra is given by:Ra $= 0.5806\ \pm 0.3098$ μm

The predicted optimal range is0.2708 μm < Ra < 0.8904 μm

(b) For average wall thickness (Th):

$f_e = 6$ (Table 5.6), $f_{\propto}(0.05, 1, 6) = 5.99$

$$\eta_{eff} = \frac{18}{1 + (5 + 2)} = 2.25$$

$$CI = \sqrt{5.99\left(\frac{1}{2.25} + \frac{1}{3}\right)0.000201} = 0.0306$$

Thus the confidence interval of the predicted optimal Th is given by:Th $= 0.9445 \pm 0.0306$ mm

The predicted optimal range is0.9139 mm < Th < 0.9751mm

(c) For wall angle deviation (Δθ):

$f_e = 6$ (Table 5.6), $f_{\propto}(0.05, 1, 6) = 5.99$

$$\eta_{eff} = \frac{18}{1 + (5 + 2)} = 2.25$$

$$CI = \sqrt{5.99\left(\frac{1}{2.25} + \frac{1}{3}\right)0.001260} = 0.0766$$

Thus the confidence interval of the predicted optimal Δθ is given by:Th $= 0.0994 \pm 0.0766$ mm

The predicted optimal range is0.0228 $^{o}$< Δθ < 0.176 $^{o}$

## 5. Confirmation of Experiment

Three confirmation trials were performed for each of the response characteristics (Ra, Th, Δθ) at optimal values of the process variables in order to validate the results obtained. The attributes' average values were collected and compared to the predicted values. The results are given in Table 13 and compared with the values of Ra, Th, and Δθ obtained through 95 % confidence intervals of confirmation experiments of respective response characteristic. It is revealed that these optimal values are within the specified range of process variables.

Table 13. Predicted and confirmation of results for responses

| Response | Surface roughness (μm) | Wall average thickness (mm) | Wall angle deviation (degree) |
|---|---|---|---|
| Optimal set of parameters | z1, d3, f1, and s1 | Z3, d3, f3, and s3 | z1, d1, f1, and s3 |
| Predicted optimal value | 0.5806 | 0.9445 | 0.0994 |
| Predicted CI at 95% confidence level | 0.2708< Ra<0.8904 | 0.9139< Th<0.9751 | 0.0228< Δθ<0.176 |
| Average of confirmation experiments | 0.57 | 0.9162 | 0.124 |

## 6. CONCLUSION

The Taguchi method's parameter design has been used to optimizethe forming processes in this research. Based on the experimental findings of this investigation, the following conclusions may be inferred:

1- The surface roughness show significant decrease with the decrease in step depthfollowed by the decrease in tool speed and slight decrease with the increase of tool diameter, while The effect of feed rate are found insignificant.

2- Average wall thickness increases with the increase of spindle speed and decreases with the increase in step depth but tool speed and feed rate are found with insignificant effect on wall average thickness.

3- The wall angle deviation significantly decreases with the increment of tool speed and with the decrement of step depth, but the tool diameter and feed rate are not significant.

4- The predicted optimal values for the surface roughness, average wall thickness, and side angle deviation are found to be 0.5806 µm, 0.9445 mm, and 0.0994° respectively

5- The confidence interval for surface roughness, average wall thickness, and side angle deviation are calculated to be 0.2708 µm < Ra < 0.8904 µm, 0.9139 mm < Th < 0.9751 mm, and 0.0228 º< Δθ < 0.176 º respectively.

6- Confirmation experiments are also carried out to ensure that the optimum forming parameters are used. The wall angle and surface roughness parameters are found to be 0.57, 0.9162, and 0.124, respectively.

**REFERENCES**


1. [1]Cui, X. H., Mo, J. H., Li, J. J., Zhao, J., Zhu, Y., Huang, L., Li, Z.W.,Zhong, K. (2014). *Electromagnetic incremental forming (EMIF): a novel aluminum alloy sheet and tube forming technology*. Journal of Materials Processing Technology, **214**(2), pp. 409-427.
2. [2]Ismail, N. A., Ismail, M. I. S., Radzman, M. A. M., Ariffin, M. K. A. M., As' arry, A. (2019). *Parametric Optimization of Robot-based Single Point Incremental Forming Using Taguchi Method*. International Journal of Integrated Engineering, **11**(1). pp. 217-224
3. [3]Cerro, I., Maidagan, E., Arana, J., Rivero, A., Rodriguez, P. P. (2006). *Theoretical and experimental analysis of the dieless incremental sheet forming process*. Journal of Materials Processing Technology, **177**(1-3), pp. 404-408.
4. [4] Lu, H. B., Li, Y. L., Liu, Z. B., Liu, S., Meehan, P. A. (2014). Study on step depth for part accuracy improvement in incremental sheet forming process. Advanced materials research, 939, pp. 274-280, Trans Tech Publications Ltd.
5. [5] Liu, Z., Liu, S., Li, Y., Meehan, P. A. (2014). *Modeling and optimization of surface roughness in incremental sheet forming using a multi-objective function*. Materials and Manufacturing Processes, **29**(7), pp. 808-818.
6. [6]Gulati, V., Aryal, A., Katyal, P., Goswami, A. (2016). *Process parameters optimization in single point incremental forming*. Journal of TheInstitution of Engineers (India): Series C, **97**(2), pp. 185-193.
7. [7] Baruah, A., Pandivelan, C., Jeevanantham, A. K. (2017). *Optimization of AA5052 in incremental sheet forming using grey relational analysis*. Measurement, 106, pp. 95-100.
8. [8] Pandivelan, C., Jeevanantham, A. K.,Sathiyanarayanan, C. (2018). *Optimization study on incremental forming of sheet metal AA5052 for variable wall angle using CNC milling machine*. Materials Today: Proceedings, **5**(5), pp.12832-12836.
9. [9] Kumar, A., Gulati, V., Kumar, P. (2018). *Investigation of surface roughness in incremental sheet forming*. Procedia computer science, 133, pp. 1014-1020.
10. [10] Kumar, A., Gulati, V., Kumar, P., Singh, V., Kumar, B., Singh, H. (2019). *Parametric effects on formability of AA2024-O aluminum alloy sheets in single point incremental forming*. Journal of Materials Research and Technology, **8**(1), pp.1461-1469.
11. [11] Mohanty, S., Regalla, S. P., Rao, Y. V. D. (2019). *Influence of process parameters on surface roughness and forming time of Al-1100 sheet in incremental sheet metal forming*. Journal of Mechanical Engineering and Sciences, **13**(2), pp. 4911-4927.
12. [12] Dabwan, A., Ragab, A. E., Saleh, M. A., Anwar, S., Ghaleb, A. M., Rehman, A. U. (2020). *Study of the Effect of Process Parameters on Surface Profile Accuracy in Single-Point Incremental Sheet Forming of AA1050-H14 Aluminum Alloy*. Advances in Materials Science and Engineering, 2020, pp. 1-14.
13. [13] Ham, M., Jeswiet, J. (2006). *Single point incremental forming and the forming criteria for AA3003*. CIRP annals, **55**(1), pp. 241-244.
14. [14] LI, J. C., Chong, L. I., ZHOU, T. G. (2012). *Thickness distribution and mechanical property of sheet metal incremental forming based on numerical simulation*. Transactions of Nonferrous Metals Society of China, 22, pp. s54-s60.
15. [15]Wang, Z., Cai, S., Chen, J. (2020). *Experimental investigations on friction stir assisted single point incremental forming of low-ductility aluminum alloy sheet for higher formability with reasonable surface quality*. Journal of Materials Processing Technology, **277**(116488), pp. 1-9.
16. [16] Obikawa, T., Satou, S., Hakutani, T. (2009). *Dieless incremental micro-forming of miniature shell objects of aluminum foils*. International Journal of Machine Tools and Manufacture, **49**(12-13), pp.906-915.
17. [17] Basak, S., Prasad, K. S., Mehto, A., Bagchi, J., Ganesh, Y. S., Mohanty, S., Sidpara, A., Panda, S. K. (2020). *Parameter optimization and texture evolution in single point incremental sheet forming process*. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, **234**(1-2), PP. 126-139.
18. [18]Antony, A. A., Ramadoss, R. (2017). *Optimization of formability parameters in incremental sheet metal forming process*. International Journal of MC Square Scientific Research, **9**(2), PP.97-107.
19. [19]Honarpisheh, M., Keimasi, M., Alinaghian, I. (2018). *Numerical and experimental study on incremental forming process of Al/Cu bimetals: influence of process parameters on the forming force, dimensional accuracy and thickness variations*. Journal of Mechanics of Materials and Structures, **13**(1), PP. 35-51.
20. [20]Echrif, S. B., Hrairi, M. (2014). *Significant parameters for the surface roughness in incremental forming process*. Materials and manufacturing processes, **29**(6), PP.697-703.