Experimental Investigations on Average Surface Roughness in Negative Incremental Sheet Metal Forming Process

Mulay A. S.\textsuperscript{a,b}, Satish Ben B.\textsuperscript{a}, Ismail S.\textsuperscript{a}, Kocańda A.\textsuperscript{b}
\textsuperscript{a}Mechanical Engineering Department, National Institute of Technology, Warangal 506004, India
\textsuperscript{b}Faculty of Production Engineering, Warsaw University of Technology, Narbutta 85, 02-524 Warsaw, Poland
\*Corresponding author. E-mail address: amrutmulay8@gmail.com

Received 01.2017; accepted in revised form 03.2017

Abstract

Single point incremental forming (SPIF) is an innovative, flexible and cost efficient process to manufacture a small batch of complex sheet metal parts. The punch produces permanent local plastic deformation imposed by CNC machine. However, this forming technology still carries few limitations. The effective study of SPIF in terms of quality production and process optimization has always been a challenge for the researchers. The surface roughness of formed product is one of the key challenges for this technique. An attempt has been made to investigate the effect of SPIF process parameters such as feed rate, step depth, tool diameter, and sheet thickness on surface roughness while forming of AA5052 H32 alloy sheet. Response surface methodology (RSM) with the Box-Behnken design is used to develop a mathematical model in terms of the above parameters. An analysis of variance (ANOVA) test shows that step depth, tool diameter and their mutual interaction has a significant effect on the surface roughness ($P < 0.0001$). The confirmation experiments were performed to check the validity of prediction model. The fractography analysis has performed at the optimum condition to understand the nature of fractured surfaces.

Keywords: Aluminum Alloy; ANOVA; Incremental Forming; Response Surface Methodology.
1. Introduction

Single Point Incremental Forming (SPIF) is highly flexible sheet metal forming process which uses rapid prototyping techniques to produce parts in small batches economically. The working principle of SPIF process is shown in fig. 1. The basic components of the process are sheet metal blank, blank holder, backing plate and rotating single point hemispherical tool. The blank holder is generally used in holding and clamping of the blank metal sheet during the process. The backing plate provides the open area during forming and it also supports the sheet metal. The single point tool rotates over the sheet and its incremental depth forms the sheet. The incremental depth and movement of the tool are controlled by CNC machine control unit. During the forming process, die sets are not used, hence, it is a cheaper process. The process is still under its development due to some limitations such as slow operation, geometrical inaccuracy, no uniform thinning of formed sheet and wavy surface texture.

Many researchers have studied the effect of SPIF process parameters on the response of sheet metal by incorporating various strategies. Cerro et al. [1] studied SPIF process by the numerical and experimental way to predict surface roughness and stress distribution in the sheet during forming. Hussain et al. [2] have found that the good surface quality of deformed pure titanium sheet is obtained by using surface hardened high-speed steel tool and molybdenum disulphide paste with petroleum jelly in a specific proportion. Shanmugananatan and Senthil Kumar [3] carried out experimental and numerical simulation to investigate maximum wall angle, surface roughness and sheet thinning of Al 3003(O). Zhaobing et al. [4] studied the impact of influential process parameters on surface roughness using the design of experiments (DOE) along with multi-objective function. Thickness distribution and failure limited diagram are studied by Malwad and Nandedkar [5] to understand the deformation mechanism behavior of commercial AA8011. Desai et al. [6] presented one factor at a time approach for dieless rapid prototyping process to study the effect of process parameters such as feed rate, tool rotational speed and incremental step depth on forming characteristics. Yanle et al. [7] performed a series of systematic test using response surface methodology (RSM) with Box- Behnken design to study the effects of the most relevant process parameters like step depth, sheet thickness, tool diameter and wall angle on both deformation energy and geometrical accuracy in incremental sheet forming process. Golabi and Hossain [8] statistically analyzed incremental forming of SS304. They studied the effect of wall angle, sheet thickness, tool diameter and vertical depth on forming height of the component. Gulati. et al. [9] focused on experimental investigation for wall angle and surface roughness based on Taguchi’s L18 orthogonal array design and concluded the effect of six different input process parameters like tool radius, sheet thickness, tool rotational speed, feed rate and lubrication on performance measures.

In the present work, the experimental plan is based on RSM combined with Box- Behnken design. An attempt has been made to establish a prediction model for average surface roughness as dependent on input process parameters. The rotational speed of tool equal to 2000 rpm is kept constant.

2. Experimental investigations

The SPIF process is carried out on three axes computerized numerical control (CNC) Oi Mate Model D/802 D SL. Vertical milling setup is shown in fig.1, where \( t_i \) is the initial thickness, \( t_f \) is the final thickness and \( h \) is the forming height. The metal sheet \( 222 \times 222 \) mm was perfectly clamped with nut and bolts at four sides to restrain movement with nut and bolts. The hemispherical end tool was employed during the process. All the tools were made up of surface hardened high-speed steel (hardness 62-65 HRC). The present work was carried out on varying wall angle conical frustum (VWACF) with circular generatrix. The wall angle at the beginning is 30° while angle at the end is 90°. The major and minor diameters of the cone are 138 mm and 78 mm respectively.

![Fig. 1. Experimental equipment and schematic representation of the SPIF process.](image)

The tool travels along the contour on the sheet surface. After completion of each contour, the tool moves down to a depth equal to the step depth and follow the next contour. The Servo 10W30 oil lubrication was used as a lubricant as it shows very good results in forming operation for aluminum alloys. Surface roughness measurement was done by Surtronic S-100 series which
was manufactured by Taylor Hobson Ametek Company. The material was selected for the experimentation is AA5053-H32 sheet. This aluminum alloy consist of 0.025, Mg; 0.26, Cr; 0.13, Si; 0.33, Fe; 0.08, Cu; 0.03, Mn; 0.03, Zn; (balance) Al by weight percentage. Due to its high strength and low weight properties, AA5052 H32 is an ideal choice in front of aerospace, automobile, and marine industries.

3. Design of experiments with Box- Behnken design

The statistical technique provides an efficient method to analyze main factor effects and factor interaction effects on system response of the process with a minimum number of experimental runs. Design expert version 9 was used to carry out analysis of variance test. In present work, RSM’s Box-Behnken design has been used for the design of experiments. RSM was introduced by G.E.P. Box and K.B. Wilson in 1951. In this design, the treatment combinations are at the midpoints of edges of the process space and at the centre. These designs are rotatable (or near rotatable). The several process parameters were studied through the pilot experimentation and it has been observed that spindle speed does not have a major influence on surface roughness characteristics. The factors with their levels are presented in table 1. The value difference between each consecutive level is the same

![Table 1. Process parameters with their values at different levels](image)

Table 2 indicates 27 set of combinations of major four influential process parameters at three levels. The lower, middle and higher levels of each factor are indicated by -1, 0, +1 respectively. The experiments were conducted according to the matrix proposed by Box-Behnken design and corresponding average surface roughness value was noted. Each experiment was conducted thrice in order to get the most precise value of the response.

4. Results and ANOVA analysis

In order to know about significant parameters affecting the SPIF process behavior ANOVA test is carried out. Analysis of variance (ANOVA) is a statistical technique for modeling the relationship between response and independent process variable. The "F value" equal to 23.49 shows that the quadratic model is well significant to predict the response parameter. There is only 0.01% chance that a “model F value” so large could occur due to noise.

![Table 2. Box-Behnken design matrix and corresponding experimental outcomes](image)
Table 3. ANOVA for response surface roughness quadratic model.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>DOF</th>
<th>Mean Square</th>
<th>F-Value</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>42.14</td>
<td>14</td>
<td>3.01</td>
<td>23.49</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>A- Feed rate</td>
<td>0.21</td>
<td>1</td>
<td>0.21</td>
<td>1.66</td>
<td>0.22</td>
</tr>
<tr>
<td>B-Step depth</td>
<td>18</td>
<td>1</td>
<td>18</td>
<td>140.51</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>C-Tool diameter</td>
<td>17.28</td>
<td>1</td>
<td>17.28</td>
<td>134.83</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>D-Sheet thickness</td>
<td>0.3</td>
<td>1</td>
<td>0.3</td>
<td>2.35</td>
<td>0.148</td>
</tr>
<tr>
<td>AB</td>
<td>0.0025</td>
<td>1</td>
<td>0.0025</td>
<td>0.019</td>
<td>0.891</td>
</tr>
<tr>
<td>AC</td>
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<td>1</td>
<td>0.01</td>
<td>0.078</td>
<td>0.784</td>
</tr>
<tr>
<td>AD</td>
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<td>1</td>
<td>0.0025</td>
<td>0.019</td>
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<tr>
<td>BC</td>
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<td>1</td>
<td>1.96</td>
<td>15.29</td>
<td>0.0015</td>
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<tr>
<td>BD</td>
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<td>1</td>
<td>0.01</td>
<td>0.078</td>
<td>0.78</td>
</tr>
<tr>
<td>CD</td>
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<td>1</td>
<td>0.04</td>
<td>0.31</td>
<td>0.58</td>
</tr>
<tr>
<td>A^2</td>
<td>0.28</td>
<td>1</td>
<td>0.28</td>
<td>2.19</td>
<td>0.16</td>
</tr>
<tr>
<td>B^2</td>
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<td>1</td>
<td>0.059</td>
<td>0.46</td>
<td>0.51</td>
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<tr>
<td>C^2</td>
<td>3.73</td>
<td>1</td>
<td>3.73</td>
<td>29.1</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>D^2</td>
<td>0.11</td>
<td>1</td>
<td>0.11</td>
<td>0.84</td>
<td>0.37</td>
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<tr>
<td>Residual</td>
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<td>14</td>
<td>0.13</td>
<td></td>
<td></td>
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<tr>
<td>Cor Total</td>
<td>43.93</td>
<td>28</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Fig. 2. Three-dimensional response surface graph and contour plot for the average surface roughness. (a, b) combined impact of step depth and tool diameter at feed rate = 1400 mm/min, sheet thickness= 1 mm; (c, d) combined impact of tool diameter and sheet thickness at feed rate = 1400 mm/min, step depth= 0.4 mm.
The coefficient of determination R-square value, in this case, is 0.9592 that is very close to 1. It shows good predictability of the developed model. In the present study B, C and $C^2$ are the most significant model terms while BC is significant. This graphical Fig. 5 that the step depth affects adversely to the surface roughness of deformed sheet. The increase in step depth causes more stress concentration in the tool-sheet interface [9]. A positive effect on the surface quality was observed at higher sized tool diameter in the experimentation. The larger tool diameter reduces waviness on the specimen due to more percentage overlapping of neighboring tool paths than smaller diameter tool.

Fig. 2 (a, b) implies the three-dimensional surface graph to represent surface roughness variation due to the interaction effect of step depth and tool diameter. The small diameter tool combined with high step depth leads to poor surface quality. The best surface roughness value is obtained at 12 mm tool diameter and 0.2 mm step depth. The average surface roughness is increased from 3.33 to 7.18 µm with 8 mm tool diameter while 2.33 to 3.38 µm with 10 mm tool diameter indicating that lower step depth was favorable for the enhancement of the surface quality of formed product. In addition to this, it shows that the process may be slightly more sensitive to change in step depth than to change in tool diameter. The effect of tool diameter and sheet thickness is depicted in fig. 2 (c, d). The surface roughness decreased from 5.29 to 4.77 µm as sheet thickness increased from 0.8 to 1.2 mm indicating that higher sheet thickness was favorable for the enhancement of the surface quality of formed product. It is obviously seen that as sheet thickness increases, surface roughness decreases.

The prediction model for surface roughness ($R_a$) in terms of actual factors is as follows:

Average surface roughness ($R_a$) = 18.81 - 1.4583E - 003 × Feed rate + 22.6458 × Step depth - 3.8791 × Tool diameter + 3.9791 × Sheet thickness + 3.1250E - 004 × Feed rate × Step depth - 6.25 × Feed rate × Tool diameter - 3.1250E - 004 × Feed rate × Sheet thickness - 1.75 × Step depth × Tool diameter - 1.25 × Step depth × Sheet thickness + 0.25 × Tool diameter × Sheet thickness + 1.3021E - 006 × Feed rate $^2$ + 2.3958 × Step depth$^2$ + 0.1896 × Tool diameter$^2$ - 3.2292 × Sheet thickness$^2$  

Further, confirmation experiments were carried out within the range of independent process parameters to validate the authenticity of the developed model. It was found that relative errors during confirmation experiments are below ±5%. Hence, this model can be considered as reliable for the surface roughness forecast while forming high strength aluminum alloy sheet. The resulting errors are within allowable limits that are small and satisfactory for engineering applications point of view. The confirmation experimental campaign authenticates the use of the RSM for optimizing the process parameters for optimizing process response in SPIF.

5. Fractography analysis

The fracture surfaces of optimum specimen was studied using scanning electron microscopy (SEM). The fractured surface at low magnification is shown in Fig. 3(a) while higher magnifications are shown in Fig. 3(b–d). The results reveal a typical ductile fracture morphology showing voids and dimples. It depicts that the material deformed plastically before the fracture has happened. It indicates that the fracture is predominantly ductile in nature. In ductile fracture, damage accumulates due to nucleation, growth and coalescence of voids.

6. Conclusions

In the presented investigation, the experimental campaign was done based on RSM's Box-Behnken design for AA 5052 H32 alloy sheet. It was successfully applied to investigate the impact of feed rate, step depth, tool diameter and sheet thickness on average surface roughness during SPIF process. It was found that surface quality heavily depends on step depth, tool diameter and their mutual interaction based on ANOVA test. The
confirmation results reveal that proposed model can be used to forecast response without expensive experimental runs. This investigation has made a framework for further research in this area.

Acknowledgements

The Author is thankful to Department of Mechanical Engineering, National Institute of Technology, Warangal for its continuous support towards carrying out research work and resolving necessary financial issues under Ministry of Human Resource Development, Government of India as well as to Department of Metal Forming and Casting, Faculty of Production Engineering, Warsaw University of Technology, Poland.

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