Original Article

Parametric effects on formability of AA2024-O aluminum alloy sheets in single point incremental forming

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\textbf{ABSTRACT}

Single point incremental forming (SPIF) is a truly die-less forming process which is quite suitable for the batch type and prototype production due to economical tooling cost, shorter lead time and ability to form nonsymmetrical geometries without using expensive dies for manufacturing complex components of sheet metal. This process mainly finds application in the medical sector, aerospace, and automotive industry. Moreover, lack of available information about formability of the process makes it limited for industrial applications. SPIF applicability can be ensured on the industrial scale when appropriate guidelines are highlighted regarding the relation between input parameters and the formability of the process. This paper insights the impact of forming tool shape, tool diameter, wall angle, step size, sheet thickness, and tool rotation on the formability of the AA2024-O aluminum alloy sheet material. Forming depth has been measured by scanning the components using a non-contact 3D scanner. Wall angle and step size have been proved more significant factors which affect the formability greatly.

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1. Introduction

Sheet metal forming has been an important manufacturing process in several industrial sectors. Mostly in the engineering field, parts are made of sheet metal particularly through conventional forming methods such as stretch forming, deep
drawing, shearing, blanking, bending, etc. These forming processes need dedicated and highly specialized equipments such as forming presses, dies, and punches. Hence, these conventional processes are expensive and time-consuming in producing sheet metal parts [1]. Moreover, small and medium volume production of precision conventional forming processes has still been a problem of the metalworking industry. Hence, manufacturing of small batch size products and prototypes are not very economical using conventional forming processes in sheet metal forming. In order to meet the production for low cost and higher quality level, a new sheet metal forming method can be used in the industries called as single point incremental forming (SPIF). This method is more suitable by virtue of shorter cycle time and economical tooling cost for the batch type and prototype production. The SPIF process is also suitable to form nonsymmetrical geometries without using expensive dies for manufacturing complex components of sheet metal at a lower cost [2]. Since localized squeeze occurs between the tool and sheet during the SPIF process; hence, the forming depth at fracture has a great impact on the precision and fracture mechanism of the sheet metal. Moreover, the stress level and forming forces of the workpiece are directly related to each other. Stress is related to the plastic strain, which calculates the structural integrity of the formed part [3,4].

Although a large amount of work has been performed in the SPIF process, still it could not have been employed in manufacturing sectors. For complex geometry, the SPIF process is more flexible and economical because of having higher formability and lesser lead time as compared to the conventional forming processes. Hence, this die-less process is much suitable in the aerospace and biomedical sectors for rapid prototyping and small-batch production [5]. This process uses simple spherical or flat-end tool which moves along the CNC controlled tool-path. It is based on deforming the sheet locally by layer [6–8].

Formability is one of the very crucial responses in the field of die-less sheet forming process which is responsible for designing of the components. For proper and safe forming of components, it is very customary to estimate the maximum formability of the parts formed during the SPIF process. There are several other reasons to investigate the formability of the components like local deformation is directly related to the plastic strain and the stress level of the work-piece which confirms the structural integrity of the formed part [4]. In the past few years, substantial research has been carried out by researchers but still, there is a lack of intensive understanding of the effects of the process parameters in the SPIF process which is very crucial in optimizing the process for better response qualities. Investigation of the formability is one of the most important ways to understand the deformation mechanism of the SPIF process. During the SPIF process, the material of the sheet fails as the forming depth of the parts rises. Hence, forming depth can be considered as an indicator of formability [9–13].

Golabi et al. [9] investigated the formability of conical frustums by analyzing the forming depth of the components. Impacts of cone diameter and sheet thickness were determined on forming depth and wall angle in the SPIF process on SS304 sheets. Results demonstrated that the increase in sheet thickness resulted in the increase in the forming depth of conical frustums. Impact of cone diameter was found negligible on the forming depth of components due to the fact that the deformation of the material is totally local during this die-less process. Formability was also found to increase with the decrease in feed rate and step size. Fiorentino et al. [10] investigated the effects of angular step size (2°, 4°, 6°) during two point incremental forming (TPIF) process on FeP04 deep drawing steel sheets. An increase in step size resulted in the decrease in the forming depth of the components. Li et al. [11] studied the effects of tool diameter on the forming depth of AA7075-O aluminum alloy sheets. A groove shape was formed until fracture of sheet material. Lora and Schaeffer [12] compared the experimental and finite element (FE) simulation results. Results were found in good agreement. Lu et al. [13] developed an analytical model in order to study the deformation behavior and formability of materials taking supporting force during squeezing and relative position of the master and slave tool into account.

Formability of the material may also be investigated in terms of maximum formed wall angle of the components [14–18]. In this approach, parts are formed until the fracture of sheet metal occurs. The maximum achievable wall angle is measured at the fracture depth. Kurrha et al. [14] investigated the formability of the extra deep drawing (EDD) steel sheets during the SPIF process in order to produce varying wall angle pyramid frustum (VWAPF) of circular, elliptical, parabolic, and exponential generatrix. Formability was measured in terms of limiting angle and fracture depth. Formability of the components was found to be higher with the elliptical generatrix. Some researchers [15–18] showed that formability of difficult to form materials can be increased with the warm conditions. Honarpisheh et al. [15] investigated the electric hot-assisted SPIF process experimentally and validated with numerical results. Results showed that the formability decreased with the increase in wall angle, step size, and tool diameter because the current density was decreased due to larger contact area between the tool and sheet which led to the decrement in the heat generation. Duflou et al. [16] studied the impact of local dynamic heating using the laser-assisted SPIF process on formability of the formed parts on 65Cr2 sheets of 0.5 mm thickness. Results showed that the parts were successfully formed till 64° wall angle using laser-assisted SPIF; whereas 57° was the limiting angle for the components produced at room temperature by SPIF process. Mohammadi et al. [17] studied the influence of different heat treatment conditions and warm forming technique on formability of the components during the SPIF process. Lehtinen et al. [18] compared the formability of the conical frustums in terms of maximum wall angle produced at room temperature and at high temperature using laser irradiation as a heating medium for aluminum, copper and deep drawing steel sheets during the SPIF process.

It is also a well-known fact that the sheet material fails for the constant wall angle frustums as the depth of the component increases. Therefore, the forming depth is an important criterion as an indicator of formability of constant wall angle frustums. In addition, sheet-thinning is less in constant wall angle frustums as compared to that in varying wall angle objects [14]. As a matter of fact, a material fails due to excessive
thinning of sheet metals during the SPIF process which is a barrier in the safe forming of the components. Material failure can be postponed by taking the constant wall angle of objects into account in order to achieve the enhanced formability. Lu et al. [13] also showed that the formability is greater for conical frustums as compared to that of pyramidal frustums for same wall angle.

Incremental sheet metal forming is characterized by different input parameters like tool diameter, wall angle, sheet thickness, step size, and tool-path etc. This die-less process is still limited to manufacturing industry due to lack of information about the process variables like tool diameter, sheet thickness, spindle speed, etc. The role of some parameters like tool-path, step size and lubrication is clear from the literature [9,10,19]. Literature [4,8,20] reports that the helical tool path provides better formability and surface quality as compared to that provided by the profile tool path. Jeswiet et al. [20] showed that the helical tool path produced the homogenous straining and thinning of material with no scratch marks. The profile tool path resulted in non-homogenous strains during the process and left the scratch marks on the surface of the workpiece. Blaga and Oleksik [21] and Thibaud et al. [22] studied effects of constant Z-level (profile) and helical tool path and revealed that helical tool path formed geometry successfully, whereas constant Z level tool path resulted in cracking sheet before the depth as obtained by helical tool path. Hence, helical tool path strategy has been adopted in the current experimental study.

Lubrication plays a vital role in the successful forming of the components during the SPIF process. It reduces friction at the contact zone of tool and sheet. Literature [1,8,11] also reports that forming oil can be effectively used as a low-cost lubricant during the SPIF process in order to reduce the friction at the tool-sheet interface. Zhang et al. [23] investigated the influences of solid lubricants (solid graphite, K₂Ti₆O₁₆ and MoS₂) with and without pulsed anodic oxidation (PAO) during hot incremental forming on magnesium alloy AZ31 sheets. PAO technique for the lubricating purpose is complex and costlier which hardly satisfies the demand of modern industries [8].

A significant knowledge about the process variables is required to obtain which would help the process engineer to implement the SPIF process in the industrial sector [24,25]. Total weight of the vehicles can be reduced in the automotive and aerospace industries with the uses of thinner sheets in place of thicker sheets without compromising their strength and stiffness. In the field of aerospace, suitable mechanical and physical properties of aluminum alloys (like low density and reduced weight without compromising with the strength of material) play a vital role in the capability and performance of the components. Al-Cu base alloy (2024) is known for its inherent property of damage control and able to retain its strength at wide temperature range [26]. Moreover, this alloy has not been investigated in the literature for the effects of tool shape, wall angle, spindle speed, and sheet thickness on the formability of the components during the SPIF process to the best of authors’ knowledge.

Taking the above issues into account, this paper focuses on the investigation of process variables on the formability of AA2024-O aluminum alloy sheets which find applications in the aerospace and automobile industries. Truncated cone-shaped parts have been formed in order to study the influence of tool diameter, sheet thickness, tool shape, wall angle, step size, and spindle speed on the forming depth. Three different shapes of forming tools have been investigated. Table 1 and Fig. 1 represent the geometry of forming tools used in this study. Table 2 shows the parameters investigated with their levels. Each parameter is studied at three levels taking other process variables constant as tool diameter 11.60 mm with the hemispherical shape, wall angle 65°, spindle speed 1000 rpm, feed rate 1500 mm/min, sheet thickness 1.2 mm, and step size 0.5 mm. Castrol lubricant oil Alpha SP 320 was applied on the sheet in order to reduce friction at the tool-sheet interface.

2. Materials and methods

2.1. Experimental set-up

Single point incremental forming tests were conducted on AA2024-O alloy sheets of size 250 mm × 250 mm. Table 3 shows the chemical composition of the alloy used in this study. An optical emission spectrometer (Foundry Master, Oxford instruments, Udedem, Germany) has been used to measure the chemical composition of the alloys taken into account. Uniaxial tensile tests were performed on a computer-controlled universal testing machine (UTM) in order to obtain the load-displacement data with a constant cross-head speed of 2.5 mm/min until fracture point. Three samples were taken out from the original sheets of each thickness along the rolling direction. Yield tensile strength, ultimate tensile strength, strain hardening exponent, and strength coefficient were recorded as output data. Average of mechanical properties of three samples along the rolling direction is presented in Table 4 for each thickness of the sheet material. In the SPIF process, the sheet material is generally deformed between yield point and ultimate tensile strength. Hence, strain hardening effects have been estimated in this region by Power law given by Eq. (1) [27].

\[ \sigma = K_0 \varepsilon^n \]  

where \( \sigma \), \( \varepsilon \), \( K_0 \) and \( n \) are true stress, true strain, strength coefficient, and strain hardening exponent respectively. It is crucial to select material and geometry (shape and size) of the forming tool for producing different workpiece shapes. In this work, high speed steel (HSS) tools have been used to investigate the effects of tool diameters and forming end radii on parts formability. Hemispherical-end and flat-end tools having lower and higher corner radii were formed and hardened to 64 HRC and then tempered before finishing the process. End radii of the forming tools were measured by a contour measuring system Contracrer CV-2100 (accuracy \( \pm (2.5 + 0.1H) \) \( \mu \)m, where \( H \) is displacement from mid-range position (mm), measurement range of detector = 50 mm, resolution = 0.1 \( \mu \)m).

A vertical machining center (Cosmos CVM-1060) with Siemens controller has been used to perform the experimental work (Fig. 2). Truncated cones of 120 mm upper diameter and 70 mm vertical depth were designed to be formed. CAD models of the truncated cone (Fig. 3) with different wall angles (60°,
Table 1 – Geometrical details of forming tools.

<table>
<thead>
<tr>
<th>Tool no.</th>
<th>Tool diameter T_D (mm)</th>
<th>Side radius of flat-end tool r (mm)</th>
<th>Radius of hemispherical-end tool R (mm)</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.52</td>
<td>1.40</td>
<td>–</td>
<td>Flat end #1</td>
</tr>
<tr>
<td>2</td>
<td>2.00</td>
<td>–</td>
<td>3.76</td>
<td>Flat end #2</td>
</tr>
<tr>
<td>3</td>
<td>–</td>
<td>–</td>
<td>5.80</td>
<td>Hemispherical</td>
</tr>
<tr>
<td>4</td>
<td>11.60</td>
<td>1.98</td>
<td>–</td>
<td>Flat end #1</td>
</tr>
<tr>
<td>5</td>
<td>2.85</td>
<td>–</td>
<td>–</td>
<td>Flat end #2</td>
</tr>
<tr>
<td>6</td>
<td>–</td>
<td>–</td>
<td>3.76</td>
<td>Hemispherical</td>
</tr>
<tr>
<td>7</td>
<td>15.66</td>
<td>1.85</td>
<td>–</td>
<td>Flat end #1</td>
</tr>
<tr>
<td>8</td>
<td>3.76</td>
<td>–</td>
<td>–</td>
<td>Flat end #2</td>
</tr>
<tr>
<td>9</td>
<td>–</td>
<td>7.83</td>
<td>–</td>
<td>Hemispherical</td>
</tr>
</tbody>
</table>

Fig. 1 – Forming tools: (a) Geometry and (b) pictorial representation.

Table 2 – Process parameters and their levels.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool diameter (mm)</td>
<td>7.52</td>
<td>11.60</td>
<td>15.66</td>
</tr>
<tr>
<td>Sheet thickness (mm)</td>
<td>0.8</td>
<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Tool shape</td>
<td>Hemispherical</td>
<td>Flatend-R1</td>
<td>Flatend-R2</td>
</tr>
<tr>
<td>Wall angle (°)</td>
<td>60</td>
<td>64</td>
<td>68</td>
</tr>
<tr>
<td>Spindle speed (rpm)</td>
<td>Free</td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td>Step size (mm)</td>
<td>0.2</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 3 – Chemical compositions of aluminum alloy used.

<table>
<thead>
<tr>
<th>Chemical compositions (weight %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA 2024-O</td>
</tr>
<tr>
<td>Al</td>
</tr>
</tbody>
</table>

Table 4 – Mechanical properties of the AA2024-O aluminum alloy sheets.

<table>
<thead>
<tr>
<th>Property</th>
<th>Sheet thickness (mm)</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate tensile strength</td>
<td>0.8</td>
<td>MPa</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td></td>
<td>243</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td></td>
<td>264</td>
</tr>
<tr>
<td>Yield strength</td>
<td>0.8</td>
<td>MPa</td>
<td>96.2</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td></td>
<td>98.4</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td></td>
<td>101.2</td>
</tr>
<tr>
<td>Strain hardening exponent (n)</td>
<td>0.8</td>
<td>MPa</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td></td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td></td>
<td>0.24</td>
</tr>
<tr>
<td>Strength coefficient (K_s)</td>
<td>0.8</td>
<td>MPa</td>
<td>390</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td></td>
<td>404</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td></td>
<td>415</td>
</tr>
</tbody>
</table>
65°, 70°) were designed by UG-NX software and then imported to DEL-CAM to prepare the part program which was directly sent to CNC controller to form the required shape. Constant wall angle conical frustums have been formed using the helical tool path. In helical tool path (Fig. 4), the tool moves both in inward radial directions (\(\Delta x\)) to take a step over, as well as in vertical direction (\(\Delta z\)) to push the sheet toward the depth of cone so that spring back effect tends to be minimum.

2.2. Methodology for measuring formability

In this study, forming depth has been considered as an indicator of formability of the formed components. Forming depth has been measured with the help of the non-contact method using a 3D scanner. Formed components were scanned by a 3D blue light scanner Smartscan\textsuperscript{3D}-HE manufactured by AICON 3D system which works on miniaturized projection technique. Fig. 5 shows the set-up for the non-contact scanning method for the cone-shaped parts using Smartscan\textsuperscript{3D}-HE blue light 3D scanner. It consists of a projection unit with the dual CCD camera, optolink, and a PC environment. Table 5 shows the specifications of Smartscan\textsuperscript{3D}-HE 3D scanner. Scanned parts

![Fig. 2 – Experimental set-up.](image-url)

![Fig. 3 – Geometry of cone shape.](image-url)

![Fig. 4 – Tool path strategy (helical).](image-url)
Scanned parts in the form of dense cloud point's model were imported to Polyworks/IMInspect software for post-processing in order to analyze the forming depth. Tables 6-8 represents experimental test results of the process parameters on the formability of conical frustums.

3. Results and discussion

Fig. 7 shows the effects of tool diameter and tool shape on the formability of the conical frustums. Formability was found to decrease with the decrease in tool diameter and tip radius.
of the forming tool. Parts were formed successfully with the tool diameter of 11.60 mm and 15.66 mm up to the designed depth without failure, whereas fractured occurred in the components which were formed with the tool diameter of 7.52 mm at the depth of 54.6 mm in case of the hemispherical tool-tip. Moreover, the hemispherical tipped tools produced better formability as compared to that produced by the FlatEnd-R1 and FlatEnd-R2 tools. These results are consistent with the technical literature [11,28]. As the tool diameter decreased, the impact of reducing side radius of flat-end tools was increased toward reducing formability.

This can be due to the fact that the smaller radius of the tool increases the penetration into the sheet and removes materials in the form of chips. Area subjected to deformation decreases at the tool-sheet interface with the smaller tool diameters which results in the increment in stress and strain levels. Hence, the smaller radius of tool-tip leads to cracking of sheet material which results in the decrement in the forming depth of the components.

3.2. Effects of wall angle and step size

Fig. 8 shows the effects of wall angle and step size on the formability of conical frustums. Formability was found to increase with the decrease in wall angle and step size. Combination of lower step size and lower wall angle resulted in the significant increment of formability. Conical frustums of 60° wall angle were formed successfully with the step sizes of 0.2 mm and 0.5 mm. As the wall angle was increased, the effect of step size increased drastically resulting in the earlier fracture of components. Wall angle and step size have become limiting factors for forming the components without fracture. Larger step size resulted in the higher stress formulation at the tool-sheet interface due to the higher requirement of forming forces to deform the material. Similarly, the higher wall angle resulted in excessive sheet-thinning according to sine law [20] which lead to earlier fracture of the sheet material.

Fig. 7 – Effects of tool diameter and tool shape on forming depth.

Fig. 8 – Effects of wall angle and step size on forming depth.

Fig. 9 – Effects of sheet thickness and spindle speed on forming depth.
3.3. Effects of sheet thickness and spindle speed

Fig. 9 shows the influence of sheet thickness and tool rotation on the forming depth of conical frustums. Formability was found to increase with the increase in sheet thickness and tool rotation. The higher sheet thickness (1.6 mm) and higher spindle speed (1500 rpm) resulted in the successful forming of the conical frustums up to the designed depth. On the other hand, the combination of lower sheet thickness and lower tool rotation led to an earlier fracture in the sheet material at a depth of 48.6 mm. Combination of larger sheet thickness and larger tool rotation increased the formability of the material significantly. These results are in accordance with [29–32] the literature. This is due to the fact the higher spindle speed increases the friction at tool-sheet contact which raises the local temperature of the sheet material. Increase in ductility of the material due to the rise in temperature results in the higher forming depth.

In case of thicker sheet, more material is available for forming which delays the crack initiation during the incremental forming of the sheet. The nature of increasing formability with the increase in sheet thickness is also related to the material’s mechanical properties. It is clear from Table 4 that the yield strength, ultimate tensile strength, strength coefficient, and strain-hardening exponent increased with the increase in sheet thickness. This stipulates that the formability of the material increases with the increase in strain hardening exponent and strength coefficient of the sheet material. This is also in accordance with [33] the literature. Moreover, strain hardening exponent provides the nature of the material to become harder and stronger during loading.

When tool diameter was decreased from 15.66 mm to 7.52 mm, formability was found to decrease by 20.29% for hemispherical, 37.95% for FlatEnd-R2, and 38.62% for FlatEndR-1 tool-shape. Formability was decreased by 42.77% for 0.2 mm, 61.63% for 0.5 mm, and 63.95% for 0.8 mm diameter when the wall angle was increased from 60° to 70°. Formability was reduced by 21.34% for 500 rpm, 16.12% for 1000 rpm, and 17.25% for 1500 rpm when the sheet thickness was reduced from 1.6 mm to 0.8 mm. Minimum formability in terms of forming depth (18.6 mm) was produced by a larger wall angle (70°) with the combination of larger step size (0.8 mm). Fig. 10 shows the successful formed and fractured components produced during this study.

4. Conclusion

In this study, the formability of AA2024-O aluminum alloy has been investigated using the SPIF process. For this purpose, conical frustums of constant wall angle have been formed in order to study the impact of process parameters. Formability was found to increase with the increase in tool diameter. Larger side radius of flat-end tools resulted in the improvement of formability of the components. Combination of flat-end tools (with lower side radius) and lower tool diameter experienced an earlier fracture in the sheet material. On the other hand, hemispherical-end tools with the higher diameter produced the components successfully without fracture. An increase in wall angle and step size led to the decrement in the formability. Combination of higher tool diameter and higher step size resulted in the fracture of components at the lower depth which is an indicator of the loss of formability. Increase in spindle speed and sheet thickness increased the formability significantly. Combination of higher spindle speed and sheet thickness resulted in the successful forming of components without fracture. The nature of increasing formability with the increase in sheet thickness is also related to the material’s mechanical properties.

Hence, the fracture forming depth can be considered and utilized as a hidden variable for modifying the process parameters by continuous comparison of crucial value and instant value for the safe forming of industrial components. Therefore, SPIF suitability can be enhanced on the industrial scale with the given guidelines regarding a relation between input parameters and forming depth. Future work would focus on the analysis of thickness distribution and forming forces of the formed components which finds importance and suitability in setting the guidelines for industrial application.
Conflicts of interest

The authors declare no conflicts of interest.

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