Study of process conditions on surface roughness in Incremental Forming Process

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Abstract: The employment of a green manufacturing process can directly save energy and materials in industrial sectors. Single Point Incremental Forming (SPIF) is an agile and flexible method of fabricating sheet material components and exempts the use of dedicated die-sets which further makes it a choice of green manufacturing. Furthermore, the customized components can be easily fabricated by SPIF economically. The surface quality of fabricated parts can greatly decide the suitability and sustainability of the process in various applications. This work investigates the impact of significant process factors on the roughness of the parts during the SPIF process. The average roughness has been considered to determine the surface quality. The increment in the value of wall angle and step size resulted in the increment in Ra value of formed components drastically. It was also observed that as the forming angle was raised from a lower level (60°) to a higher level (68°), the Ra value was found to increase significantly.

Keywords: Incremental Sheet Forming, Single Point Incremental Forming, Surface Roughness, AA2024, Input Parameters

1. Introduction
In the modern era, the needs of customers change very rapidly which allows the production units to manufacture the customized parts economically to upgrade their business. Complex and end-user parts of sheet material can be easily fabricated by batch-type production with lower cycle-time and cost to accomplish the requirements of customers [1-2]. Sheet forming techniques are widely used for manufacturing parts with negligible wastages for different applications. However, conventional methods of sheet forming produce the hindrance to customized production because of the involvement of dedicated die-sets to produce the specific shape. Moreover, the conventional forming techniques require the utilization of larger and heavy machinery to fabricate sheet material components [3-5].

Hence, a flexible and agile method of forming the sheet material into desired shapes is highly appreciated to produce the customized components economically. Such a technique can positively fabricate the customized parts economically to fulfill the need of various frontier sectors. Incremental Sheet Forming (ISF) is a flexible and agile process of forming the customized parts of sheet material economically and efficiently. This method of forming excludes the use of forming dies and punches which makes it economically suitable for batch-type and customized production. In this variant of forming, a simple forming tool can fabricate a variety of complex shapes on a single forming set-up. The forming tool is moved on the surface of sheet material which deforms the sheet material layer by layer using the predetermined numerical instructions on forming machinery, normally CNC milling machine [6-8]. The CAD model of the designed geometry of components is usually imported in suitable CAM software to prepare the numerical instructions for the CNC milling machine in the form of G-
codes. The origin of the ISF process was established by Mason’s [9] in 1978. However, related work was also reported in two patents [10, 11] issues in 1967. The ISF finds wider application including automobile components, aero-foil fuselage parts, ankle and knee implants, cranial plate, customized channels, etc. [12-13].

Single Point Incremental Forming (SPIF) is a type of ISF technique that simply removes the direct and indirect need of any type of die-sets and is known as “negative incremental forming” or “die-less forming”. Moreover, the absence of dedicated dies turns this process into a flexible and agile method of forming that enhances the viability of this process for rapid prototyping. Fig. 1 illustrates the principle of this die-less technique.

Figure 1. The schematic of Single Point Incremental Forming [1]

The forming force required to deform the sheet material is significantly low in SPIF as compared to traditional forming approaches which directly saves power up to a great extent as smaller size machinery can be used to fabricate the sheet material components. Hence, SPIF can be referred to as a choice of green manufacturing. The surface roughness of the parts produced by forming processes is of great significance to increase the readiness of the process to the mainstream of industrial and commercial sectors. The investigation of impact factors of SPIF techniques on surface roughness of formed components can ensure the efficient implementation of this die-less process. Although, some work has been investigated by researchers towards surface roughness of components formed by ISF that is not significant to impart the effects of process parameters.

Mulay et al. [14] explored the influence of process factors like the diameter of the tool, the thickness of the sheet, step down, and feed rate on surface roughness using AA5052-H32 Al alloy sheets. It was found that punch radius and step size were the most contributing factor for surface roughness. Kumar and Gulati [15] explored the input variables for average roughness and found that the tool radius, tool geometry, and viscosity of forming oil were the most contributing factors. They also provided the statistical model to predict the average roughness. Vijaya et al. [16] investigated the effects of step size, wall angle, and tool material on the surface roughness of IS513 Cr3 sheet. It was observed that to obtain a good surface finish, tool diameter was kept at a higher value and step depth was kept at a lower value. Kumar et al. [17] studied the impact of tool rotation and tool radius on surface quality and found that the combination of higher tool rotation and higher tool radius produces good surface quality during SPIF operation. Dabwan et al. [18] also investigated the influence of various parameters on surface profile. It
was found that a better surface finish was achieved with lower sheet thickness, the larger diameter of the tool, and minimum step down. Mohanty et al. [19] also studied the effects of various process parameters on surface roughness on Al-1100 alloy sheets. Higher surface roughness was observed for a higher forming angle and feed rate. Kumar et al. [20] studied the impact of tool shape and tool radius on surface quality and found that the combination of flat-end tool and higher wall angle produced poor surface quality. Wang et al. [21] investigated the effect of local temperature in friction stir-assisted ISF on the surface quality of AA2024-T3 alloy sheets. Surface roughness was estimated by two types of scales namely fish scale & cutting scale.

Literature reports that the investigation of wall angle and step size and the effects of their interactions on surface roughness has not been studied significantly. Furthermore, the SPIF process has not been implemented in the mainstream manufacturing industries because of a lack of proper guidelines about the influence of impact factors which affect the surface roughness of formed components significantly. The knowledge about the impact of wall angle, step size, and their interactions on the surface quality of formed parts during SPIF would open the new window for implementing this technique in manufacturing units. Therefore, it becomes crucial to perform the experimental campaign to explore the significance of crucial input variables on the surface quality of formed parts. Furthermore, AA2024-O is an important alloy that can be widely used in various sectors including aerospace, automobile, medical, and architects because of its favourable characteristics like greater toughness, resistance to corrosion, the ability of damage control, moderate hot hardness, and lightweight. The current study attempts on investigating the impacts of wall angle, step size, and their interactions on average roughness on AA2024 sheets. These input variables and their interactions have not been explored on AA2024 alloy sheets for average surface roughness so far. Table 1 delineates the varied input variables with their levels. Furthermore, Table 2 delineate the geometrical details of forming tool and Table 3 represents the process parameters that have been fixed during experimental work.

Table 1. The levels of input variables under investigation

| Parameter        | Level 1 | Level 2 | Level 3 | Level 4 |
|------------------|---------|---------|---------|---------|
| Wall angle (°)   | 60      | 64      | 68      | -       |
| Step size (mm)   | 0.2     | 0.5     | 0.8     | 1.2     |

Table 2. Geometrical details of forming tools

| Tool diameter | Side radius of flat-end tool |
|---------------|-------------------------------|
| T₀ (mm)       | r (mm)                        |
| 11.60         | 2.85                          |
| Tool Shape    | Flat end with side radius    |
Table 3. The constant input factors undertaken in the study

| Factor         | Value      | Unit |
|----------------|------------|------|
| Tool shape     | Flat end   | -    |
| Tool diameter  | 11.60      | mm   |
| Sheet thickness| 1.2        | mm   |
| Step size      | 0.5        | mm   |
| Feed rate      | 1500       | mm/min |
| Spindle speed  | 1000       | RPM  |
| Lubricant      | Castrol Alpha SP 320 | - |
| Tool path      | Helical    | -    |

2. Materials and methods
The experimental set-up was prepared on a CNC milling machine as shown in Fig.2. The forming tool was mounted in the spindle of the CNC milling machine. The SPIF fixture was clamped on the table of the milling machine. The sheet specimen was fixed in the SPIF fixture. Conical frustums of 120 mm major diameter and 70 mm height were selected as the component which was designed in SOLIDWORKS® software. Delcam™ software was taken into account for generating the numerical instructions for forming the conical frustums using a helical tool path.

Figure 2. Experimental set-up on CNC milling machine

To analyze the surface characteristics, the average surface roughness (Ra) value was considered. A roughness measuring device (Mitutoyo SJ-400) was used for measuring the Ra value of formed components as shown in Fig.3. For enhancing the measuring statistical accuracy of formed frustums,
each formed part was measured four times and the average value is reported in Table 4. The formed component was fixed with the help of a magnetic V-block on the measuring arrangement (see Fig.3) and the stylus was allowed to move on the inner surface of the conical frustum. The Ra value was recorded from the display unit.

![Figure 3. Surface roughness measurement set-up](image3)

3. Results and discussion

Table 4 shows the experimental results of average surface roughness (Ra) according to the full factorial approach as the design of experiment. The influence of the interaction of wall angle and step size is depicted by Fig.4.

![Figure 4. Impact of wall angle and step size on average roughness](image4)
Table 4. Experimental results of average roughness of formed components

| Run | Step size | Wall angle | Ra (μm) |
|-----|-----------|------------|---------|
| 1   | 0.2       | 60         | 0.63    |
| 2   | 0.2       | 64         | 0.73    |
| 3   | 0.2       | 68         | 0.88    |
| 4   | 0.5       | 60         | 0.74    |
| 5   | 0.5       | 64         | 0.84    |
| 6   | 0.5       | 68         | 0.99    |
| 7   | 0.8       | 60         | 0.87    |
| 8   | 0.8       | 64         | 0.99    |
| 9   | 0.8       | 68         | 1.16    |
| 10  | 1.2       | 60         | 1.07    |
| 11  | 1.2       | 64         | 1.22    |
| 12  | 1.2       | 68         | 1.39    |

The increment in the forming angle and step size resulted in the increment in the Ra value of formed components drastically because for higher wall angle, higher lateral part of tool tip comes in contact with sheet material during the forming process which leads to the formation of the steeper surface of the designed part. Hence, surface waviness is increased for producing higher wall angle and step size. The Ra value was found to be minimum (0.63 μm) when the step size and wall angle were kept at a lower level as 0.2 mm and 60° respectively. Fig.5 shows the component formed with minimum Ra value during run 1. On the other hand, the Ra value was noticed to be maximum (1.39 μm) when the step size and wall angle were kept at a higher level as 1.2 mm and 68° respectively.

Figure 5. Component formed successfully with good surface finish during run 1 (Ra value 0.63 μm, step size 0.2 mm, wall angle 60°)
Moreover, a higher step size (1.2 mm in this case) resulted in the fracture of sheet material at a depth of 16.32 mm of the component when it was employed with the wall angle of 68° respectively as shown in Fig. 6. It was also observed that when the wall angle was increased from a lower level (60°) to a higher level (68°), the Ra value was found to increase by 39.68 %, 33.78 %, 33.33 %, and 29.90 % for the step size of 0.2 mm, 0.5 mm, 0.8 mm, and 1.2 mm respectively. Similarly, the Ra value was noticed to rise by 69.84 %, 67.12 %, and 57.95 % for the wall angle of 60°, 64°, and 68° respectively when the step size was raised from 0.2 mm to 1.2 mm. Moreover, the Ra value was observed to rise by 120.63 % when the experimental condition was changed from the combination of lower levels of wall angle (60°) and step size (0.2 mm) to the combination of higher levels of wall angle (68°) and step size (1.2 mm).

Figure 6. Fracture of the sheet during run 12 with bad surface quality (Ra value 1.39 μm, step size 1.2 mm, wall angle 68°)

4. Conclusion
The current work explored the surface quality of the component formed during the SPIF technique. The interactions of these factors were also studied while fabricating the conical frustums from AA2024 alloy sheets using a helical tool path. Results showed that both of the factors affect the surface roughness of formed components significantly. Average roughness was noticed to rise with the increase in wall angle and step size. The Ra value was found to be minimum when the step size and wall angle were kept at a lower level as 0.2 mm and 60° respectively. On the other hand, the Ra value was noticed to be maximum when the step size and wall angle were kept at a higher level as 1.2 mm and 68° respectively. Moreover, the Ra value was noticed to rise by 120.63% when the experimental condition was changed from the combination of lower levels of wall angle (60°) and step size (0.2 mm) to the combination of higher levels of wall angle (68°) and step size (1.2 mm). Future work will target the mechanism of significant factors on thinning limit and microstructure of formed parts.
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