Exploration of wall angle and tool rotation on surface roughness in Negative Incremental Forming Process

Ajay Kumar1*, Amit Kumar2, Amit Kumar1, Shikha Gupta3, Rakesh Rajpal2, Prateek Srivastava4
1Department of Mechanical Engineering, Faculty of Engineering & Technology, Shree Guru Gobind Singh Tricentenary University, Gurugram 122505, Haryana, India
2Department of Mechanical Engineering, Ganga Technical Campus, Soldha, Bahadurgarh, Haryana, India
3Department of Humanities, Delhi Technological University, New Delhi, India
4Chitkara University Institute of Engineering and Technology, Chitkara University, Punjab, India

E-mail address: ajay.kumar30886@gmail.com

Abstract: A significant augmentation in the obsolescence of traditional forming techniques results in the strong requirement of developing an emerging and flexible process to fabricate the user-ready parts in the manufacturing units. Single Point Incremental Forming (SPIF) also known as “negative incremental forming” has shown its viability as a novel and emerging forming method for fabricating the customized and batch-type products of sheet materials to satisfy the need of various potential sectors including medical, automobile, and aerospace. This method directly exempts the involvement of dedicated die-sets and turns into the choice of green manufacturing. The surface quality of fabricated parts can greatly decide the suitability and sustainability of the process in various applications. In the current study, the impact of wall angle and tool rotation have been explored for surface roughness during SPIF. Results revealed that the increase in spindle speed resulted in the decrease of Ra value of formed components. Moreover, the Ra value of formed components was found to decrease by 50 % when the experimental condition was changed from the combination of higher levels of wall angle and “free-to-rotate” condition of spindle speed to the combination of lower levels of wall angle (60°) and a higher level of spindle speed (1500 rpm).

Keywords: Incremental Sheet Forming, Single Point Incremental Forming, Surface Roughness, AA-2024, Input Parameters

1. Introduction

The manufacturers are adopting several production approaches for producing batch-type and customized products according to the need of consumers for upgrading their business. Also, the production of components of complex and intricated geometries must be furnished at lower cost and cycle-time to make the fabrication procedure economical [1, 2]. The various industrial sectors involve sheet material components that are usually fabricated by different forming methods. The sheet forming processes generates a negligible amount of wastage during production. Although, the conventional sheet forming methods offers a hindrance to batch-type manufacturing because of the involvement of dedicated die-sets to produce the specific shape. Furthermore, the involvement of heavy and specific die-sets leads to the employment of bigger-size machinery to accomplish the fabrication of sheet components [3-5]. Therefore, a flexible and novel method of sheet forming can become a benchmark for fabricating the customized and batch-type components of sheet materials economically. Incremental Sheet Forming (ISF) is the flexible process of forming the components of sheet materials for different applications including automobile, medical, and aerospace without involving dedicated die-sets. A single forming
set-up can potentially fabricate various intricate shapes using a simple forming tool which is actuated over the sheet with suitable step size and feed contour by contour using the numerical instruction on any milling machine or industrial robot [6-8]. The numerical instructions are normally prepared by CAM packages for the designed CAD model of the desired shape to be produced. 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 and fuselage parts, ankle and knee implants, cranial plate, customized channels, etc. [12, 13]. Single Point Incremental Forming (SPIF) is one of the kinds of ISF which is the purely die-less method of forming and is also called “negative incremental forming”. The working principle of the negative incremental process is shown in Fig.1.

![Figure 1. The schematic of Single Point Incremental Forming [1]](image)

Moreover, the negative incremental forming method needs a smaller amount of forming load to produce the deformation on sheet material that directly reduces the power and energy of forming equipment and hence can be referred to as a choice of green manufacturing. The surface roughness of sheet material components can play a vital role in enhancing the suitability of this die-less method to the various industrial units. The study of process variables of negative incremental forming on the surface quality of the fabricated parts can open various windows for the researchers to increase the suitability of this at an industrial scale. However, 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.

It has been noticed from the literature report that the interactions of wall angle and spindle speed have not been explored significantly during SPIF. 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, spindle speed, 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 favorable characteristics like greater toughness, resistance to corrosion, the ability of damage control, moderate hot hardness, and lightweight [22]. The current study attempts on investigating the impacts of wall angle, spindle speed, 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 geometrical details of forming tool. Furthermore, Table 2 delineates the varied input variables with their levels 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      | -       |
| Spindle speed (rpm)| Free    | 500     | 1000    | 1500    |

Table 2. Geometrical details of forming tools

| Tool diameter | Side radius of flat-end tool |
|---------------|-----------------------------|
| TD (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 |
| Lubricant   | Castrol Alpha SP 320 | - |
| Tool path   | Helical     | -      |

2. Materials and methods

A CNC milling machine was used for fabricating the designed components of sheet metal as shown in Fig.2. The workpiece was firmly fixed in the hollow fixture that was further mounted on the table of the milling machine. The forming tool was firmly mounted in the collate and spindle of the machine tool. The truncated conical shape was selected as a benchmark that was designed using Solidworks® software. The numerical instructions, for CNC milling, were generated with the help of DelcamTM software using a helical type tool trajectory.

Figure 2. Experimental set-up on CNC milling machine

The average surface roughness (Ra) value has been taken into account to determine the surface characteristics. Mitutoyo SJ-400 device was utilized for measuring the Ra value of the conical frustums as shown in Fig.3. Each component, under investigation, was measured four times for increasing the measuring statistical accuracy of formed frustums 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

3. Results and discussion

The experimental results of Ra value have been presented in Table 4 according to the full factorial approach as Design of Experiment (DOE). The influence of the interactions of wall angle and spindle speed has been delineated by Fig. 4. The increase in wall angle resulted in the increment in the Ra value of formed components because, for higher wall angle, a higher lateral part of tooltip comes in the contact of 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 a higher wall angle. On the other hand, the increase in spindle speed resulted in the decrease of Ra value of formed components because the increase in tool rotation allows the proper lubrication at the tool-sheet interface during forming which reduces the scratching action on the surface of the sheet. This trend was consistent with all levels of the tool rotation. The combination of lower wall angle (60° in this case) and higher tool rotation (1500 rpm in this case) resulted in the minimum Ra value (0.64 μm) of the formed component. Fig. 5 shows the component formed with minimum Ra value during run 10. The combination of higher wall angle (68° in this case) and lower tool rotation (“Free-to-rotate” condition in this case) resulted in the maximum Ra value (1.26 μm) of the formed component. Furthermore, this combination (run 3, in this case) resulted in the fracture of sheet material at a depth of 18.22 mm of the formed component.

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 27.27 %, 26.37 %, 28.94 %, and 28.57 % for the spindle speed of free-to-rotate, 500 rpm, 1000 rpm, and 1500 rpm respectively. On the other hand, the Ra value was found to decrease by 36.36 %, 35.77 %, and 35.71 % for the wall angle of 60°, 64°, and 68° respectively when the spindle speed was raised from “free-to-rotate” condition to 1500 rpm. Moreover, the Ra value of formed components was found to decrease by 50 % when the experimental condition was changed from the combination of higher levels of wall angle (68°) and “free-to-rotate” spindle speed to the combination of lower levels of wall angle (60°) and a higher level of spindle speed (1500 rpm).
Figure 4. Influence of wall angle and spindle speed on average roughness

Table 4. Experimental results of average roughness of formed components

| Run | Spindle speed | Wall angle | Ra (μm) |
|-----|---------------|------------|---------|
| 1   | Free          | 60         | 0.99    |
| 2   | Free          | 64         | 1.09    |
| 3   | Free          | 68         | 1.26    |
| 4   | 500           | 60         | 0.91    |
| 5   | 500           | 64         | 1.00    |
| 6   | 500           | 68         | 1.15    |
| 7   | 1000          | 60         | 0.76    |
| 8   | 1000          | 64         | 0.84    |
| 9   | 1000          | 68         | 0.98    |
| 10  | 1500          | 60         | 0.64    |
| 11  | 1500          | 64         | 0.70    |
| 12  | 1500          | 68         | 0.81    |
4. Conclusion
This work studied the interactions of wall angle and spindle speed on the surface quality of conical frustums that were fabricated using the SPIF process on a CNC milling machine. The flat-end tool was used as a forming agent. Furthermore, a helical tool trajectory was taken into account for producing the conical frustums from AA 2024 alloy sheets. A full factorial approach was taken into account as DOE. Results showed that both of the factors affect the surface roughness of formed components significantly. The increase in wall angle resulted in the increment in the Ra value of formed components. On the other hand, the increase in spindle speed resulted in the decrease of Ra value of formed components because the increase in the tool rotation allows the proper lubrication at the tool-sheet interface during forming which reduces the scratching action on the surface of the sheet. The combination of lower wall angle (60° in this case) and higher tool rotation (1500 rpm in this case) resulted in the minimum Ra value (0.64 μm) of the formed component. Moreover, the Ra value of formed components was found to decrease by 50 % when the experimental condition was changed from the combination of higher levels of wall angle (68°) and “free-to-rotate” spindle speed to the combination of lower levels of wall angle (60°) and a higher level of spindle speed (1500 rpm). The future work would target the effects of relevant parameters on thickness reduction and formability of components.

References
[1] Ajay, Mittal, R. K.: Incremental Sheet Forming Technologies: Principles, merits, limitations, and applications, 1st edn. CRC Press, Taylor and Francis, ISBN: 978-0-367-27674-4. United States (2020).
[2] Sakhtemanian, M. R., Honapisheh, M., Amini, S.: A novel material modeling technique in the single-point incremental forming assisted by the ultrasonic vibration of low carbon steel/commercially pure titanium bimetal sheet, The International Journal of Advanced Manufacturing Technology 102, 473–486 (2019).
[3] Kumar, A., Gulati, V., Kumar, P., Singh, V., Kumar, B., Singh, H.: Parametric Effects on Formability of AA2024-O Aluminum Alloy Sheets in Single Point Incremental Forming. Journal of Materials Research and Technology, 8(1), 1461-1469(2019).
8

[4] Kumar, Ajay, Vishal Gulati, Parveen Kumar, Hari Singh, Vinay Singh, Sanjay Kumar, and Abid Haleem. "Parametric Investigation of Forming Forces in Single Point Incremental Forming." Materials Today: Proceedings 24 (2020): 611-617.

[5] Kumar, A., Gulati, V.: Forming Force in Incremental Sheet Forming: A Comparative Analysis of the State of the Art. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 41 (2019).

[6] Zhai, W., Li, Y., Cheng, Z., Sun, L., Li, F., Li, J.: Investigation on the forming force and surface quality during ultrasonic-assisted incremental sheet forming process. The International Journal of Advanced Manufacturing Technology 106, 2703–2719 (2020).

[7] Kumar, A., Gulati, V., Kumar, P.: Investigation of Process Variables on Forming Forces in Incremental Sheet Forming. International Journal of Engineering and Technology 10(3), 680-684 (2018).

[8] Kumar, A., Gulati, V.: Experimental investigations and optimization of forming force in incremental sheet forming. Sadhanā 43, 159 (2018).

[9] Mason, B.: Sheet metal forming for small batches. PhD Thesis, Univ. of Nottingham (1978).

[10] Leszak, E., Ave, H.: Apparatus and process for incremental dieless forming. United States Patent, United States (1967).

[11] Berghahn, W. G., Murray, G. F.: Method of dieless forming surfaces of revolution. United States Patent, New York (1967).

[12] Kumar, Ajay, and Vishal Gulati. "Optimization and investigation of process parameters in single point incremental forming." (2020). Vol. 27, pp. 246-255.

[13] Kumar, A., Gulati, V., Kumar, P.: Experimental Investigation of Forming Forces in Single Point Incremental Forming. In: Shanker, Kripa, Shankar, Ravi, Sindhwani, Rahul (eds.) International Conference on Future Learning Aspects of Mechanical Engineering 2018, LNME, pp. 423-430. Springer, (2019).

[14] Mulay, A., Ben, S., Ismail, S., & Kocanda, A. (2017). Experimental investigations into the effects of SPIF forming conditions on surface roughness and formability by design of experiments. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 39(10), 3997-4010.

[15] Kumar, A., Gulati, V.: Experimental Investigation and Optimization of Surface Roughness in Negative Incremental Forming. Measurement: Journal of the International Measurement Confederation (131), 419-430 (2019).

[16] Vijayakumar, M. D., Chandramohan, D., & Gopalamasubramanian, G. (2020). Experimental investigation on single point incremental forming of IS513Cr3 using response surface method. Materials Today: Proceedings, 21, 902-907.

[17] Kumar, A., Gulati, V., Kumar, P.: Investigation of Surface Roughness in Incremental Sheet Forming. In: Procedia Computer Science, International Conference on Robotics and Smart Manufacturing 2018, vol. 133, pp. 1014-1020. Elsevier (2018).

[18] 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.

[19] 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), 4911-4927.

[20] Kumar, A., Gulati, V., Kumar, P.: Effects of Process Parameters on Surface Roughness in Incremental Sheet Forming. In: Materials today proceedings, International Conference on Composite Materials, Manufacturing, Experimental Techniques, Modeling and Simulation 2018, vol. 5(14), pp. 28026-28032. Elsevier, (2018).

[21] 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.

[22] Kumar, A., Kumar P., Gulati V. Singh Y., Singh V., Mittal R. K. (2021). Impact of Step Size, Spindle Speed and Sheet Thickness on Forming Force in SPIF, R. K. Phanden et al. (eds.), Advances in Industrial and Production Engineering, Lecture Notes in Mechanical Engineering, pp. 917-926. Springer, (2021).