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Research Article

Experimental Study of Sheet Incremental Forming Process with Controlled Movement of Material into the Forming Cavity

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ABSTRACT

Incremental forming is one of the methods for single-piece forming of metal sheets. In the conventional configuration of this process, the sheet is held fixed between holders, preventing any movement toward the forming cavity. Since the presence of draw beads in deep drawing dies controls the material flow into the die, thereby reducing defects such as wrinkling and thinning, this study incorporates this feature into the design of the holders in sheet incremental forming. Experimental tests were conducted both with and without the bead, and the effect of its presence on sheet thickness variation and forming accuracy was evaluated. In this context, with a different definition of the bead performance, its positive role in the incremental forming process is also noticeable, with the distinction that the blank holder's role is to control the contact surface between the sheet and the holders and to regulate friction. Experimental observations confirm that in the case of linear contact between the holders and the workpiece through a double bead, controlled movement of the sheet into the cavity is possible, which in turn reduces thinning by approximately 30% while maintaining forming accuracy.

1. Introduction

The sheet incremental forming (SIF) process is a flexible method for single production and prototyping without the need for dedicated dies. In the traditional single-point type of this process, which is performed on a CNC milling machine, the workpiece is fixed between blank holders and mounted on the machine table. A hemispherical-headed tool gradually forms the sheet by following closed toolpaths and applying vertical pressure. As shown in Fig. 1, the tool moves along a helical path with specified axial and radial steps, gradually descending from the top toward a conical-shaped surface. This movement continues from the outermost point of the sheet surface toward the center and finishes at the desired depth.

The values of axial and radial step size, feed rate, tool rotational speed, type of lubrication, sheet material and thickness, and tool characteristics are among the process

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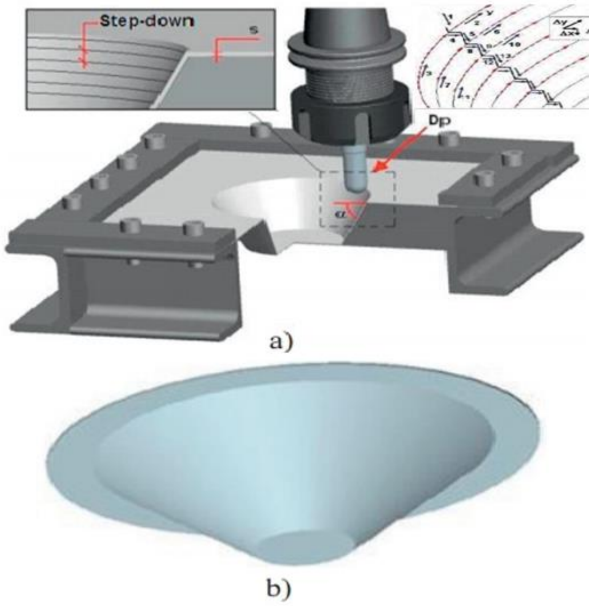

Fig. 1. Schematic of the single-point incremental forming (SIF) method.

parameters that affect the quality of the produced workpiece. Among the quality indicators in this process are sheet thinning, dimensional accuracy, and the microstructure of the workpiece.

A group of researchers has sought process variables that improve these quality indicators. Hamilton and Jesswitt [1] found that under high rotational speeds and feed rates, the thickness distribution and microstructure are similar to those observed at lower speeds. In the study by Mirnia et al. [2], using sequential limit analysis and experimental validations, it was found that increasing the tool diameter leads to increased tensile strain and reduced thickness. Furthermore, increasing the vertical step size up to a certain limit improves thinning. Ghasemi and Soltani [3], through an experimental study of forming an aluminum truncated pyramid, found that reducing the tool rotation speed improves the minimum thickness. Additionally, employing a helical tool path helps achieve a more uniform thickness distribution. Mohammadi et al. [4], using numerical simulation, showed that increasing the tool diameter and vertical step size leads to greater thinning, while the coefficient of friction between the tool and the sheet has little effect on the thickness distribution. Song et al. [5] investigated micro single-point incremental sheet forming (SPISF), analyzing formability and thickness distribution in aluminum foils while evaluating critical process parameters. They also proposed a direct relationship between forming angle and material formability [6]. Kumar and Gulati [7] researched forming forces in single-point incremental forming (SPIF) to optimize process parameters including sheet thickness, tool geometry, and feed rate for conical frustum production. Mezher et al. [8] explored the incremental sheet forming (ISF) of hole-flanged parts in AA1060 aluminum and DC01 steel sheets. Barimani-Varandi et al. [9] investigated rapid prototyping of aircraft canopies using incremental forming of polycarbonate sheets, analyzing tool rotation effects on transparency and toolpath strategies on geometric accuracy. Karim et al. [10] analyzed thickness evolution and geometric accuracy in SPIF-formed truncated pyramids using DOE and GTN damage modeling, identifying forming angle as the most critical parameter affecting thickness reduction (error <4%) and springback. Said et al. [11], analyzed key aspects including process parameters, tooling, formability, and simulation techniques to enhance flexibility and precision. Kharche and Barve [12] reviewed single point incremental forming (SPIF) applications for non-metallic materials, analyzing formability of various polymers (PVC, PET, PC, etc.) and investigating PA-6 composites through simulation and experimental studies. Yang et al. [13] developed a room-temperature flexible free incremental sheet forming (FFISF) method for titanium alloys (TA2/TC4), to optimize tool paths and auxiliary sheets for defect-free fabrication. Prasad et al. [14] examined incremental sheet metal forming (ISMF) for processing lightweight alloys, analyzing critical parameters like tool path and geometry on formability and accuracy.

Another group of researchers demonstrated that by performing the process in multiple stages, the process indicators can be improved. Yang and Kim [15] introduced a two-step process in which regions that undergo less deformation in the first step experience greater deformation in the second step, and vice versa. They showed that with the two-step process, the thickness distribution improves, leading to increased sheet formability. Mango et al. [16] and Mirnia et al. [17] studied the three-step process. In the best case, thinning decreased by 23% compared to the single-step condition. However, Mango and colleagues [16] reported a negative impact on the dimensional accuracy of the part in this process under special conditions. The five-step incremental forming process was examined by Duflou and colleagues [18]. The intermediate shapes were considered with an increase in wall angle of 10° at each step. According to them, using multiple forming steps instead of a single step can be a strategy to delay premature thinning. One of the drawbacks of this strategy is the bulging of the bottom of the container.

The third group of researchers has attempted to improve the aforementioned indicators by adding ultrasonic vibrations to the tool [19] or by heating the sheet [20-21]. Yang et al. [22] developed a novel heat-assisted incremental sheet forming method for PEEK sheets, analyzing forming forces, geometric accuracy, and fracture mechanisms through pyramid frustum experiments with CWA and VWA approaches. Trzepieciński et al. [23] reviewed recent advancements (2015-2021) in incremental sheet forming (ISF) technologies for lightweight alloys, analyzing conventional and thermally-assisted ISF processes with focus on tool-sheet contact conditions and surface quality. Tabasum et al. [24] investigated the formability of GLARE fiber metal laminates in hydromechanical deep drawing, demonstrating that stepwise-increasing variable cavity pressure (VCP) achieved superior results with a maximum forming depth of 29.00 mm while preventing wrinkling, delamination, and fracture. Shang et al. [25] advanced hydraulically-supported incremental forming strategies to improve thickness distribution in thin-walled parts, demonstrating that hydrostatic pressure below 1.8 bar outperforms conventional methods while variable-pressure approaches may offer further enhancements. Tiwari et al. [26] developed a hybrid additive manufacturing-incremental forming (HAMIF) process that integrated material deposition with in-situ forming. They demonstrated through COMSOL simulations how their innovative extrusion system with variable-pitch screws and thermal control enabled simultaneous AM-IF operations. Vignesh et al. [27] conducted a comprehensive review of the incremental sheet forming (ISF) process, focusing on its deformation mechanisms and recent advancements like heat-assisted and water jet ISF. They also detailed the process's application to various materials and discussed the distinct advantages and limitations of each variant. Palwai et al. [28] developed a novel frequency decomposition method using Fourier transform to algorithmically design preforms for multi-stage Robo-forming, significantly improving forming depth for complex shapes like a cranial implant by up to 235% without fracture. Their work provides a standardized, non-heuristic approach to overcome the critical wall angle limitation in incremental sheet forming.

In all previous studies, the sheet was held firmly between two holders. The authors' hypothesis in this paper is that controlled movement of the sheet into the forming cavity will somewhat reduce the sheet thinning. This can be considered a generalization of the use of draw bead in the deep drawing process. In Fig. 2, two common types of beads in the deep drawing process are shown. Material flows when passing through the bead zone. The bead provides sufficient restraining force with minimal damage or reduction in the material's formability. In deep drawing with a bead, the punch’s advancement into the die causes an increase in sheet thickness, and if this continues, wrinkling of the sheet occurs. The result of wrinkling is the lifting of the upper blank holder, which leads to an increase in the distance between the lower and upper holders. In this case, a resisting force is generated by the bead and by a specific area of contact of the sheet with the holder.

Shallow beads are generally used more frequently because deeper beads lead to increased friction forces due to greater surface contact with the die.

In this study, an attempt has been made to use beads to permit the movement of the sheet into the forming cavity in order to investigate their effect on thinning and dimensional accuracy of the workpieces. For this purpose, tests were conducted both in the absence and presence of the bead, and the results were compared.

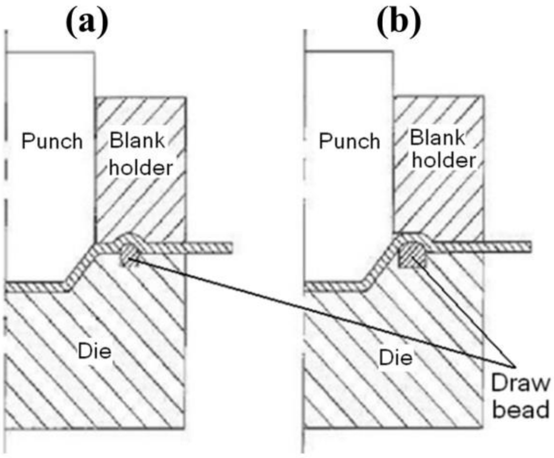

Fig. 2. Schematic design of (a) intermediate bead and (b) edge bead [29] in the deep drawing process.

2. Experimental Method Setup

In Fig. 3(a), the traditional configuration of the SIF process is shown, including a cross-sectional front view of the sheet, blank holders, and tool at the start and end of the process. The edge of the initial sheet is perforated at the screw locations so that four fastening screws can pass through and secure the sheet between the two holders. Obviously, in this case, the compressive force of the nuts and the weight of the upper holder prevent the sheet from flowing into the forming cavity through friction, while the screws mechanically restrain the sheet's movement.

According to Fig. 3(b), traditional edge beads used in the deep drawing process has been applied in SIF. The protrusions and recesses of this type of bead, in the form of upper and lower rings have been machined and fitted into the corresponding slot, allowing for the rings to be replaced and the bead radii to be fabricated. The normal force is proportional to the tightening of the nuts and the compression of the springs. Since it was observed in the tests that under various conditions this configuration did not allow the sheet to move into the forming cavity, a new configuration was employed as shown in Fig. 3(c).

In this case, due to the line contact of the bead's protrusion with the underside of the sheet, friction with the lower holder is reduced. The results show that under certain conditions, the sheet can move into the forming cavity in this configuration. After confirming the sheet's flowability in the single bead configuration, the final setup was proposed according to Fig. 3(d) (double bead), and supplementary tests were conducted. In this new form of bead application in the SIF process, it is expected that by reducing the contact surface between the sheet and the holders, the compressive force can be adjusted to control the sheet displacement.

Fig. 4 shows the setup of the holders and the workpiece on the machine table. A sample of the formed workpieces is also shown in this figure. The tests were conducted on a 3-axis CNC milling machine branded SADRAFAN GOSTAR^{TM}- SMG, with a motion resolution of 0.01 mm for each axis and a motor power of 400 W.

Fig. 5 shows the springs used. To ensure sheet displacement, the back of the initial blank was sprayed black. In Fig. 6, a sample of the formed workpieces is shown, which has a strip of faded paint due to the sheet sliding over the bead. If the sheet had no possibility of displacement, as in the traditional process, this strip would not appear.

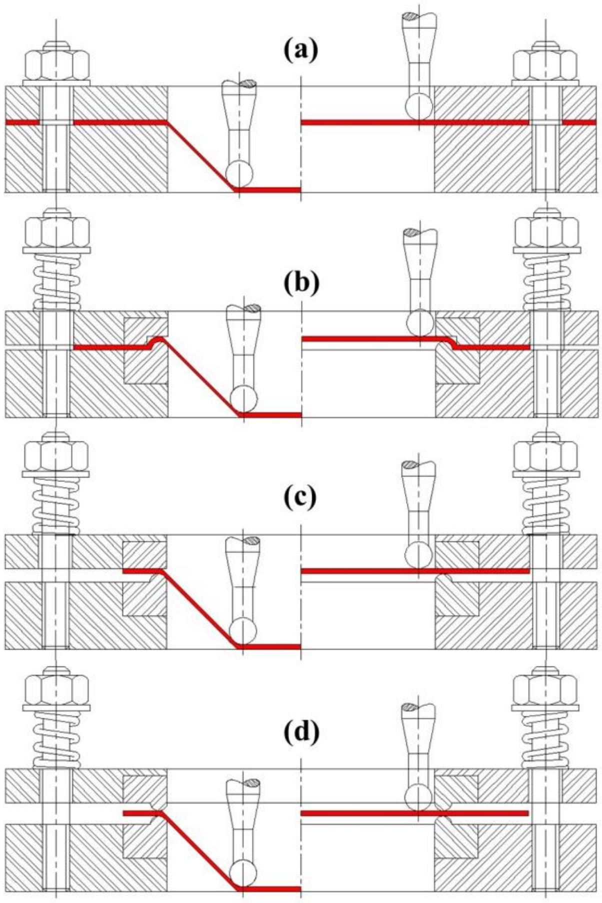

Fig. 3. Configurations of (a) traditional SIF, (b) holders with traditional edge bead, (c) single SIF bead, and (d) double SIF bead at the start (right) and end (left) positions.

Fig. 4. Installation of the specialized SIF tooling set on the milling machine.

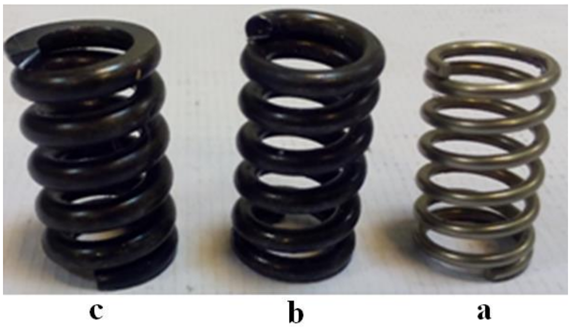

Fig. 5. Three sizes of compression springs used in the tests.

Fig. 6. Visibility of sheet displacement inside the die during forming.

The material of the tested sheet was 1000 series aluminum. The shape of the workpiece was a truncated cone with a height of 32 mm and different wall angles. The initial blank diameter was 100 mm in the traditional type, and between 70 –87 mm in the other tests. After each test, the surface of the workpiece was scanned using a COMET5 3D scanner (Fig. 7). Following surface fitting and cross-sectioning, the actual wall angle was measured (Fig. 8).

Table 1 lists the process variables and their levels of variations in tests. Table 2 presents the parameters that were kept constant across different tests based on hardware capabilities and previous researchers' reports.

Fig. 7. Scanning of the formed parts using a 3D scanner.

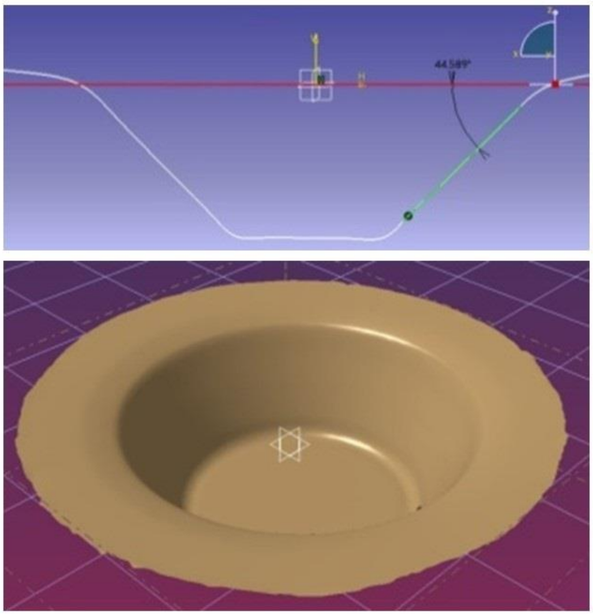

Fig. 8. Surface fitting on the scanned point cloud and measurement of the actual wall angle of the part using CAD software.

Table 1. Process variables and their levels of variation in the tests

Variable parameters	Selected values		
Sheet thickness (mm)	0.5	1	1.5
Bead radius (mm)	2.5	5	7.5
The angle of forming (Degree)	45	65	85
Lubricant type	Without lubricant	Cellophane	SAE 40

Table 2. Constant parameters in the tests

Constant parameters	Selected values
Tool diameter (mm)	8
Feed rate (mm/min)	800
Tool rotational speed (rpm)	1000

3. Results and Discussion

The tests conducted in this study were designed to demonstrate the impact of the presence of a bead on the quality of SIF parts and to assess the effect of each factor. A total of approximately 200 tests were carried out in seven sections. In each case, three repetitions were performed and the results were averaged. Each part was scanned once in 3D and geometrically modeled, and its thickness was measured twice along the radial direction. After confirming the controlled displacement of the sheet with a new definition of the bead in the SIF process, the roles of spring characteristics, bead radius, presence of lubricant, wall angle, sheet thickness, and the size of the contact surface between the sheet and holders were evaluated. At each stage, the most favorable conditions were selected for the next phase of the study.

3.1. Effect of bead presence

In the first section, tests were conducted using three different process configurations as shown in Fig. 3(a), 3(b), and 3(c). The sheet thickness in these tests was 1 mm, and the wall angle was 65 degrees. As shown in Fig. 9, there is little difference in wall thickness variations between the absence and presence of the traditional edge bead, since sheet displacement and thickness changes are negligible. Due to the localized and small forming force applied in SIF, the force required to overcome friction and flatten the bent sheet at the bead location is not provided. However, by eliminating the sheet bending at the bead location (Fig. 3(c)) and reducing the contact surface and normal force, it was observed that the sheet is drawn into the forming cavity, resulting in a 32% reduction in thinning. However, approximately a 6% thickness reduction was also created in the middle region of the sample, which had not occurred previously in this process.

In Fig. 10, it can be seen that the angular deviation of the part's wall after completion of the process in the presence of a single bead (Fig. 3(c)) is reduced by approximately 63% compared to the condition without a bead. With the reduction in thinning and consequently decreased elastoplastic deformation, springback is also reduced. This is also somewhat true in the case of the edge bead. Therefore, the introduced single bead plays a positive role by reducing thinning and angular deviation of the wall, whereas the traditional edge bead from the deep drawing process does not provide such performance for SIF.

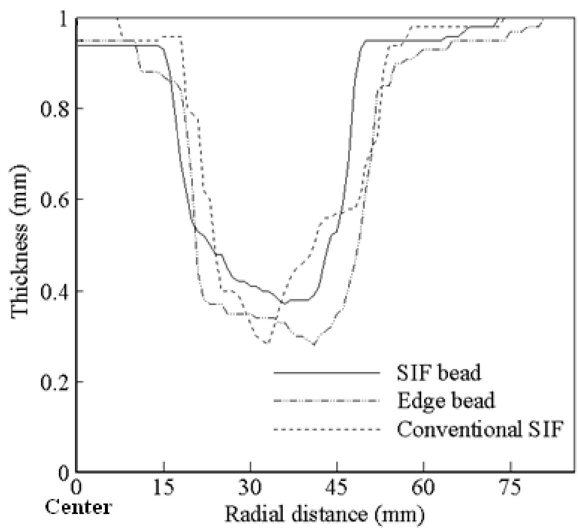

Fig. 9. Radial thickness variations of the part with and without the presence of a bead.

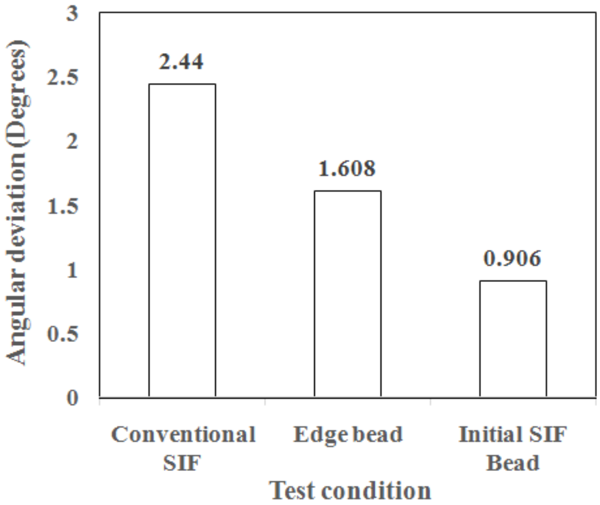

Fig. 10. Angular deviation of the wall from the design value with and without the presence of a bead.

3.2. Effect of the spring

The spring allows for adjusting the normal force and consequently the friction between the sheet and holders so that the sheet is drawn into the forming cavity in a controlled manner. For controlled tightening of the nuts in the configuration shown in Fig. 3(c), the best method is to use a suitable torque wrench. However, considering the test conditions—including the dimensions and material of the holders as well as the size and surface quality of the workpieces—the required force is not high. Due to the unavailability of a small torque wrench, three different springs were used (Fig. 4). The steel rod diameters used in these three types of compression springs were 1.5, 2.5 and 3 mm, respectively, and their force-displacement curves are plotted in Fig. 11. The minimum force required to initiate the process for sheets with thicknesses of 0.5 mm, 1 mm, and 1.5 mm were provided using springs with rod diameters of 1.5 mm, 2.5 mm, and 3 mm, respectively. These forces have optimal values for each sheet thickness; if the force is lower, the sheet slips inside the holders and the process cannot continue, and if it is higher, thinning will increase. To achieve the above-mentioned springs and pressing forces, several tests were conducted using different sheets and springs. The wall angle in these tests was set to 45 degrees. In subsequent tests, the same springs were used for forming the aforementioned sheets.

3.3. Effect of bead radius

To study the effect of bead radius, three different sizes, as described in Table 1, were used. Fig. 12 shows the three rings used, each with a circular protrusion and selected radii. In the conducted triple tests, the sheet thickness was 1 mm and the cone wall angle was 45 degrees. Fig. 13 and 14 present the results. It can be observed that by reducing the bead radius by 66%, from 7.5 mm to 2.5 mm, thinning decreased by 3% and angular deviation was reduced by 90%. With the reduction of bead radius and contact surface, friction moved toward an optimal value. At the start of tool movement, due to the axial force applied, the sheet bends over the bead surface, which increases friction. This bending is less at smaller bead radii. Easier sheet displacement consequently leads to reduced thinning.

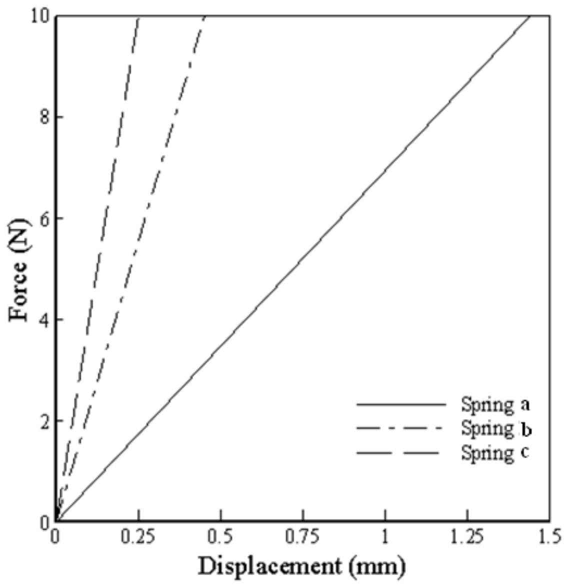

Fig. 11. Force-displacement curves of springs a, b, and c shown in Fig. 5.

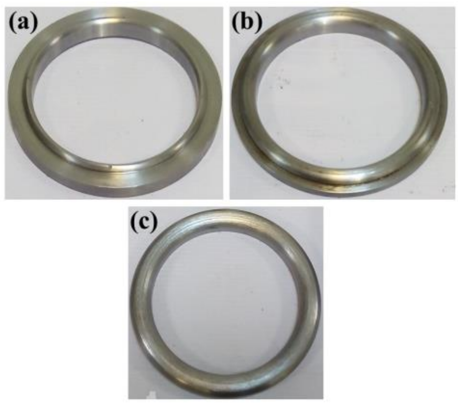

Fig. 12. Beads with radii of (a) 2.5 mm, (b) 5 mm, and (c) 7.5 mm.

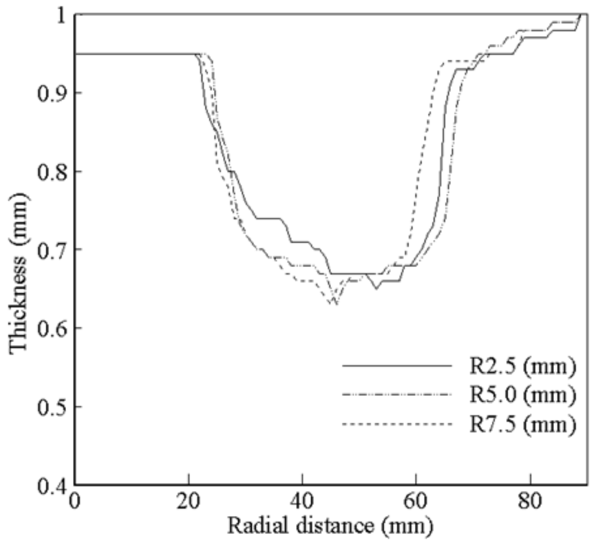

Fig. 13. Radial thickness variations of the part corresponding to different bead radius.

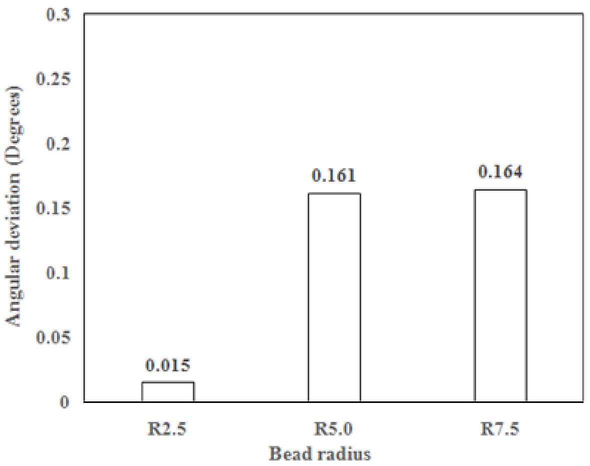

Fig. 14. Angular deviation of the wall from the design value with different bead radius.

3.4. Effect of using lubricant

In the traditional SIF process, it is common to use oil as a lubricant between the tool and the sheet. Whenever the goal is to control the material flow into the forming cavity, the friction between the sheet and the holders becomes an influential parameter. Based on this, tests were conducted using three types of lubricants applied to the upper contact surface of the sheet (Fig. 3(c)). In these tests, a 1 mm thick sheet with a 45° wall angle and a 2.5 mm bead radius was used. The forming process was carried out either dry, with oil, or using a plastic film (cellophane) as a lubricant. Fig. 15 and 16 show the quality of the samples. These figures reveal that although the use of oil reduces thinning by approximately 3%, the angular deviation of the wall increases by about 88% compared to the dry condition. It appears that when using oil, the sheet's freedom of displacement after the process is excessive, which makes the dry condition perform better in this regard.

3.5. Effect of wall angle

In Fig. 17, it can be seen that thickness variations increase with the wall angle for 45° and 65°. This trend continues for the 85° angle as well; however, the full height cannot be achieved at this angle, and the sheet tears at a depth of ~10 mm. Increasing the wall angle

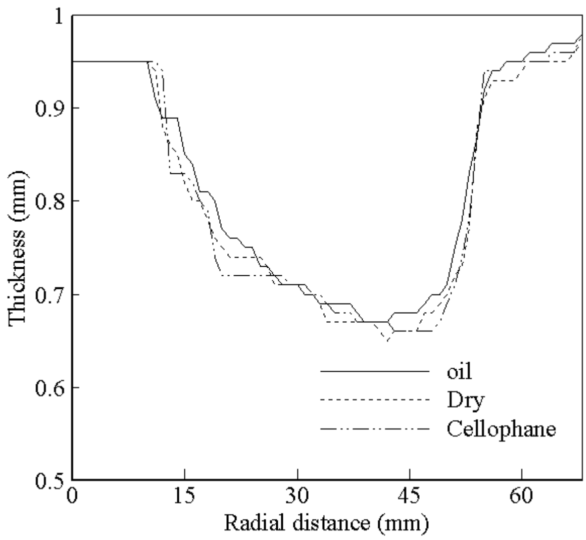

Fig. 15. Radial thickness variations of the part under different lubrication conditions.

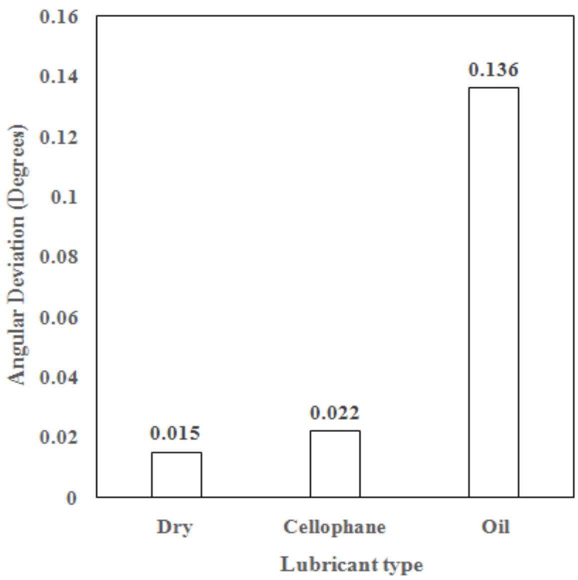

Fig. 16. Angular deviation of the wall from the design value under different lubrication conditions.

leads to greater strain and thickness variation. Consequently, as the angle increases, the dimensional accuracy of the formed part decreases (Fig. 18). Naturally, with the increase in total elastic-plastic deformation, the elastic and thus reversible portion of deformation also becomes larger. In this section, sheets with a thickness of 1 mm, a bead radius of 2.5 mm, and dry lubrication conditions were used. With a 44% increase in the wall angle from 45° to 65°, thinning increased by approximately 44% and angular deviation increased by 84%.

3.6. Effect of sheet thickness

To investigate the effect of sheet thickness on the quality of sample parts, tests were conducted using three thicknesses: 0.5, 1 and 1.5 mm. In these tests, the wall angle was set to 45 degrees. Fig. 19 and 20 show the amount of thinning and forming accuracy, respectively. It is observed that with approximately a 50% increase in sheet thickness, thinning increases by about 2%. It is worth noting that during the forming of the 1.5 mm sheet, some burrs were observed alongside the tool's progression and it is expected that part of the thinning is due to the aforementioned chip removal. As the thickness decreases, the forming accuracy increases (Fig. 20). It seems that the raw aluminum sheet production process has influenced the results, and due to more extensive rolling of the 0.5 mm sheet, higher strain hardening occurred, resulting in less springback and thus higher forming accuracy.

3.7. Effect of contact surface

In the tests from sections 1 to 4, it was observed that by reducing the contact surface area, the sheet's displacement during the process increases. Essentially, to control the sheet flow and friction, reducing the contact surface between the sheet and the holders allows the variables to be simplified to controlling the normal force.

To achieve this goal, the holder configuration was modified according to Fig. 3(d). As expected, for the sheet with 0.5 mm thickness under the new bead setup, the sheet displacement increased, resulting in reduced thinning as shown in Fig. 21. Whenever preventing

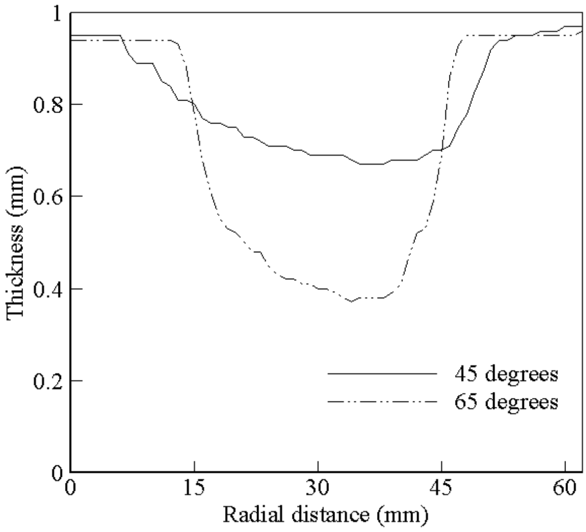

Fig. 17. Radial thickness variations for different wall angles.

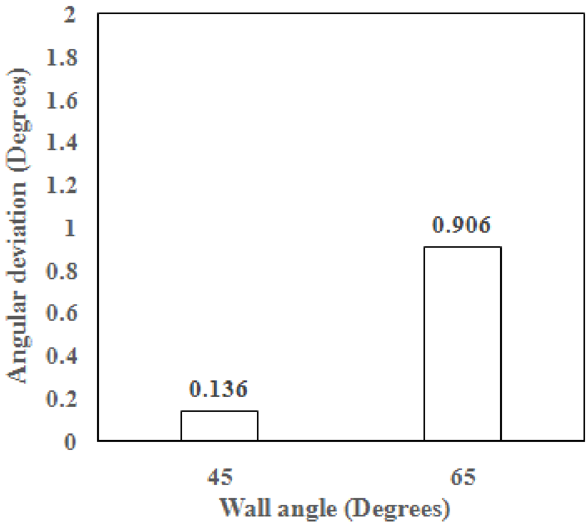

Fig. 18. Angular deviation of the wall from the design value with varying wall angles.

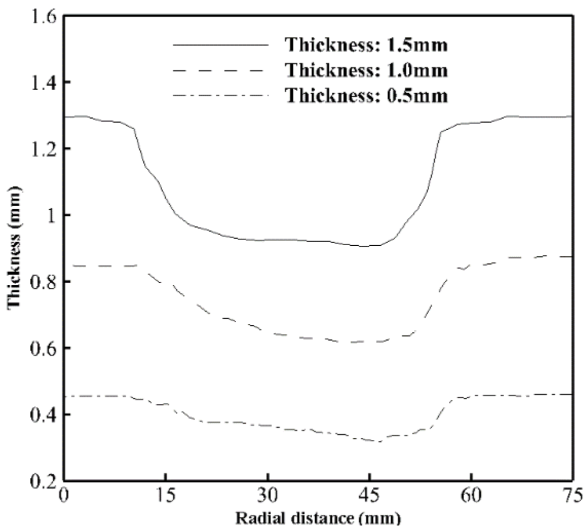

Fig. 19. Radial thickness variations of the part for different sheet thicknesses.

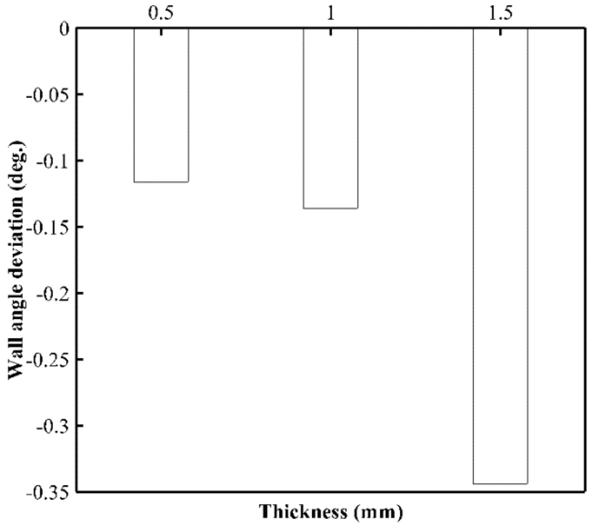

Fig. 20. Angular deviation of the wall from the design value with changing sheet thickness.

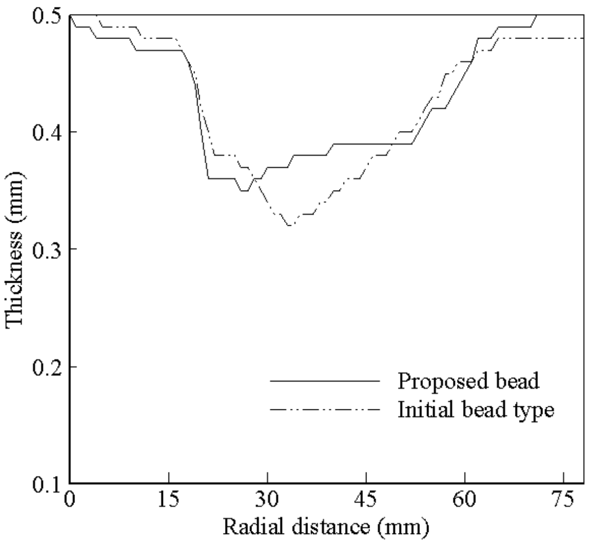

Fig. 21. Radial thickness variations of the part with single and double beads.

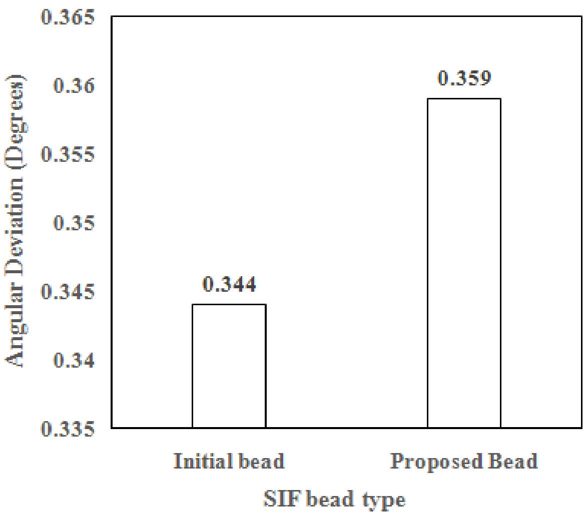

Fig. 22. Angular deviation of the wall from the design value with changes in bead type.

tearing is the main objective of the process; this bead configuration is more favorable. Additionally, as observed in Fig. 22, the angular deviation of the wall increases by 4% when using the new bead, because a larger area of the material undergoes deformation, resulting in greater springback.

4. Conclusions

In this study, by generalizing the positive role of the drawing bead in the deep drawing process, this element was added to the design of the holders in the SIF process. With a new definition of the blank holder's function, the bead's role in the SIF process is also significant, with the difference that in SIF, the blank holder's role is to control the contact area between the sheet and the holders, as well as to regulate friction. When a double bead is used in the upper and lower blank holders, the contact changes from area to linear contact, and the main controlling variable of sheet movement becomes the friction force. There is a certain friction force under which the sheet thinning is minimized, and the angular accuracy of the part does not change significantly. It is predicted that with this configuration, sheet tearing will be significantly delayed. A smaller bead radius is more suitable for controlling movement, and the use of lubricant affects the amount of thinning. Increasing the thickness reduces the percentage of thickness variation, while increasing the wall angle causes it to increase.

Author's contributions

S. J. Hemmati: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Project administration, Writing - original draft

M. R. Kamranfard: Methodology, Supervision, Software, Resources, Validation, Writing - original draft

M. Moridi: Visualization, Writing - review & editing

Competing interests

The authors declare that they have no known competing interests.

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Data availability

All data generated or analyzed during this study are included in this published article.

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