

A study on a novel flexible sheet forming process based on incremental plunge

Huiting Wang

wgwht@ahut.edu.cn

Anhui University of Technology

Xing Chen

Xiaohui Shen

Hongbo Pan

Research Article

Keywords: Incremental sheet forming, Incremental plunge forming, Surface roughness, Surface morphology, Forming limit

Posted Date: September 30th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10455907/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

During the Incremental Sheet Forming (ISF) process, the continuous sliding contact between the forming tool and the sheet surface often results in poor surface finish, characterized by directional grooves and severe friction marks. To overcome this limitation, a novel method named Incremental Plunge Forming (IPF) is proposed, in which the forming tool intermittently plunges into and retracts from the sheet along a programmed trajectory, replacing continuous sliding with localized pulsating plunge. Experiments were conducted on AA5754 aluminum alloy sheets with a thickness of 0.8 mm using a conventional three-axis CNC milling machine. The results demonstrate that IPF can successfully form complex cone-shaped and variable-angle parts with satisfactory geometric accuracy. Compared with conventional SPIF, IPF produced a distinctive honeycomb-like surface texture instead of the conventional record-groove pattern. The average surface roughness (R_a) was reduced from 1.116 μm for SPIF to 0.4 μm for IPF under the same lubrication conditions, representing a reduction of approximately 64%. Additionally, the forming limit angle of IPF reached 80°, slightly exceeding the 79° obtained by conventional SPIF. These findings indicate that IPF is a viable die-less forming method that simultaneously improves surface quality and formability.

1. Introduction

Incremental Sheet Forming (ISF) is a flexible die-less forming process in which a hemispherical or ball-end forming tool, guided by a CNC machine, progressively deforms a clamped sheet metal blank into a desired three-dimensional shape through a series of localized plastic deformation steps [1, 2]. Because ISF does not require dedicated dies or punches, it offers significant advantages for rapid prototyping, small-batch customization, and economically viable production of complex sheet components in sectors such as aerospace, automotive, biomedical devices, and architecture [3, 4]. Since the pioneering work of Matsubara on single-point incremental forming (SPIF) in the 1980s [5], extensive research has been conducted to understand the deformation mechanics, optimize process parameters, improve geometric accuracy, and broaden the range of applicable materials [6–9].

Despite these advances, the industrial uptake of ISF remains constrained by several persistent technical challenges. Among them, the relatively poor surface quality of formed parts is widely recognized as a critical limitation [10, 11]. In conventional SPIF, the tool tip maintains continuous contact with the sheet and slides along a helical or contour path. This continuous sliding action generates severe friction, localized temperature rise, and mechanical ploughing, which manifest as regular, directional grooves on the formed surface—commonly described as “record-groove” texture [12, 13]. Such surface defects not only degrade aesthetic appearance but can also act as stress concentrators, potentially reducing fatigue life and corrosion resistance [14, 15].

The root cause of the inferior surface finish in SPIF lies in the nature of the tool–sheet interaction. The forming tool continuously presses and drags the material along the tool path, producing both longitudinal grooves from mechanical ploughing and inter-layer ridges from the step-down between

successive contour passes [16]. These effects are particularly pronounced when forming aluminum alloys, where adhesive wear and material transfer may further aggravate surface damage [17]. Consequently, any process modification that alters the continuous sliding contact mode offers a potential route to improved surface integrity.

Several variants of ISF have been proposed to address different aspects of the process. Luo et al. [21, 22] proposed an incremental punching system in which a high-speed hydraulic punch head was used to deform the sheet metal punch by punch and layer by layer. Their work focused on the development of a mechanics model based on the minimum energy principle for shape prediction [21] and the design and building of a prototype machine with experimental verification of formability and thickness distribution [22]. The incremental punching concept demonstrated that intermittent deformation can produce complex free-form parts without bottom support. However, their study did not investigate the surface quality aspects of the formed parts – an aspect that is critical for industrial acceptance, particularly in applications where surface integrity directly affects functional performance such as fatigue resistance, wear behavior, and corrosion protection.

Other researchers have explored different approaches to improve ISF surface quality. Durante et al. [23] investigated the influence of tool rotation on surface roughness, finding that higher spindle speeds could reduce friction-related surface damage. Fan et al. [24] studied the effect of process parameters on surface roughness using response surface methodology. Ajajar et al. [25] reviewed various process variants and highlighted that surface quality remains one of the least addressed aspects in ISF research. Despite these efforts, a fundamental approach – changing the contact mode from continuous sliding to discrete indentation – has not been systematically studied with respect to its effects on surface morphology, surface roughness, and formability.

Motivated by the above considerations, the present study proposes Incremental Plunge Forming (IPF) as a variant of ISF that specifically targets surface quality improvement through a fundamental change in tool-sheet contact mechanics. While the concept of intermittent punching was introduced by Luo et al. [21, 22] and realized using a CNC machine retrofitted with a custom-built hydraulic punching system, the present work utilizes the plunge milling function of a standard CNC milling machine to realize the IPF approach.

2. The principle of the novel method

The fundamental difference between conventional SPIF and the proposed IPF lies in the relative motion between the forming tool and the sheet blank. In SPIF, the tool follows a continuous spiral or contour path and remains in constant sliding contact with the sheet, as illustrated in Fig. 1(a). In contrast, the IPF tool follows a discontinuous “plunge–retract–translate–plunge” trajectory, as shown in Fig. 1(b). Each plunge cycle induces a localized plastic indentation; the cumulative effect of many such indentations along successive layers gradually builds the desired three-dimensional geometry.

The IPF process sequence can be described as follows. First, the sheet blank is clamped onto a backing plate or fixture mounted on the CNC machine table, and a ball-end forming tool is installed in the machine spindle (Fig. 2). A custom CNC program is then generated according to the target geometry by utilizing the function of plunge milling manufacture module and adjusted by tool compensation function, specifying the in-plane feed increments, the plunge depth per layer, and the retract height between successive plunges. During forming, the spindle moves the tool downward along the Z-axis until the tool contacts and indents the sheet; after reaching the programmed plunge depth, the tool retracts to a preset safe height, moves in the X-Y plane to the next position, and performs the next plunge. This cycle is repeated until one contour layer is completed, after which the tool steps down in the Z-direction and the next layer is processed. Through layer-by-layer accumulation of localized plastic deformation, the final part geometry is obtained.

A key distinction between IPF and conventional SPIF lies in the deformation mechanics at the tool-sheet interface. In SPIF, the tool continuously slides along the sheet surface, and the material undergoes a combination of stretching, bending, and shear deformation under sustained contact. The friction between the tool and the sheet generates heat and produces directional grooves aligned with the tool path. In IPF, each plunge event is essentially a localized indentation process, during which the tool penetrates the sheet vertically and then retracts. The material beneath and around the tool tip experiences predominantly compressive deformation, with limited lateral sliding. Between successive plunges, the tool is fully retracted from the sheet, eliminating continuous frictional interaction. This intermittent contact mode is expected to reduce frictional heat generation, minimize adhesive wear, and produce a fundamentally different surface texture characterized by overlapping indentations rather than continuous grooves.

3. Materials and Experimental setup

3.1. Material properties

The material used in this study was AA5754 aluminum alloy sheet supplied in the O-temper (annealed) condition, with a nominal thickness of 0.8 mm. Square blanks measuring 120 mm × 120 mm were cut from the as-received sheet by a shearing machine. Table 1 lists the measured mechanical properties of the AA5754 sheet. The mechanical properties were obtained from uniaxial tensile tests conducted along the rolling direction at a constant crosshead speed of 2 mm/min using standard dog-bone specimens prepared according to ASTM E8.

Table 1
Mechanical properties of the 0.8 mm AA5754-O
sheet used in this study.

Property	Value	Unit
Yield strength, $\sigma_{0.2}$	110	MPa
Ultimate tensile strength, σ_{UTS}	220	MPa
Elongation to fracture, δ	18	%
Young's modulus, E	70	GPa
Hardness, HV	62	HV

3.2. Experimental equipment and process parameters

All forming experiments were performed on a conventional three-axis CNC milling center. A cemented carbide ball-end tool with a diameter of 10 mm was used as the forming tool. The tool was held stationary (non-rotating) during the IPF process to ensure pure indentation without rotational sliding. No backing die or partial die was employed, so the process remained fully die-less. This setup differs from the dedicated hydraulic punching machine used by Luo et al. [22], which featured a high-speed hydraulic cylinder capable of 300 strokes per minute. The use of a standard CNC milling machine in the present study demonstrates that IPF can be implemented on widely available equipment without specialized hardware.

The CNC tool paths were manually programmed according to the target geometry using plunge milling function, and subsequently adjusted by tool compensation function in order to obtain right machining trajectory. The following process parameters were used for the IPF experiments: depth per cut (step-down) $\Delta z = 0.5$ mm, step forward (in-plane feed increment) = 0.5 mm, tool plunge depth equal to the depth per cut, and retract height between plunges = 2 mm. For the conventional SPIF comparison experiments, identical depth per cut and feed rates were used, but the tool followed a continuous helical path without intermediate retraction. No. 45 mechanical hydraulic oil was applied to the tool-sheet interface for both SPIF and lubricated IPF trials; an additional unlubricated IPF trial was also conducted for comparison. The process parameters used in this study are summarized in Table 2.

Table 2
Summary of process parameters used in the experiments.

Parameter	SPIF	IPF
Tool path	Continuous helical	Discrete plunge-retract
Depth per cut, Δz (mm)	0.5	0.5
Step forward (mm)	0.5	0.5
Retract height (mm)	N/A	2.0
Tool diameter (mm)	10	10
Tool rotation	Stationary	Stationary
Lubrication	With/without	With/without
Blank size (mm)	120 x 120	120 x 120
Sheet thickness (mm)	0.8	0.8

3.3. Surface roughness measurement

Surface roughness was measured using a Jingguan TR200 portable surface profilometer. Measurements were taken on the inner wall of the formed cones, approximately midway between the top and bottom edges, along both the circumferential (perpendicular to the tool path) and meridional (parallel to the tool path) directions. For each condition, at least three replicate measurements were performed at different angular positions, and the arithmetic mean roughness R_a and maximum height of profile R_z were recorded. The cutoff length and evaluation length were set to 0.8 mm and 4.0 mm, respectively, in accordance with ISO 4287.

3.4. Surface morphology characterization

In addition to quantitative roughness measurements, the surface morphology of the formed parts was examined using optical microscopy and digital photography. Top-view and close-up images were captured for both SPIF and IPF specimens to characterize the surface texture patterns. The surface morphologies were analyzed qualitatively with respect to texture directionality, regularity, and the presence of defects such as grooves, ridges, indentations, and material transfer marks.

4. Results and Discussion

4.1. Evaluation of the feasibility and effectiveness of the new process

To verify the basic feasibility of IPF, a preliminary forming test was first conducted using a shallow concave geometry. As shown in Fig. 3, the IPF process successfully produced a contoured part with a

smooth inner profile and a formed depth of approximately 12 mm. The sidewall exhibited regular circumferential ridges produced by the layer-wise indentation sequence, but no tearing, wrinkling, or severe thinning was observed. This preliminary result confirms that the intermittent plunge-retract motion can accumulate localized plastic deformation in a controlled manner and form a continuous three-dimensional shape, consistent with the findings of Luo et al. [22] for their incremental punching system.

To further assess the geometric forming capability and accuracy of IPF, conical parts with wall angles of 45° and 60° were formed using the IPF process. Figure 4 shows representative parts formed at these two angles. Visual inspection and manual measurement revealed that the conical sidewalls were straight and that the transition between the wall and the base was smooth. The side wall of the 60° cone remained in close contact with a straightedge placed along the generatrix, indicating satisfactory straightness and overall shape fidelity. These results demonstrate that IPF can achieve geometric accuracy comparable to that expected from conventional SPIF for axisymmetric cone geometries.

The successful formation of these geometries also demonstrates that the plunge-retract tool path strategy, despite its discontinuous nature, can produce continuous and smooth surfaces. This is because the overlapping of adjacent indentation zones, controlled by the in-plane feed increment, ensures that the material between successive plunge points is sufficiently deformed to form a continuous profile. The relationship between the feed increment, tool radius, and surface continuity is analogous to that in conventional SPIF, where the step-down distance determines the inter-layer ridge height.

4.2. Comparison of surface states and characteristics of machined parts

Figures 5 and 6 compare the surface morphologies of parts formed by conventional SPIF and IPF, respectively. The SPIF surface exhibits a series of regular, continuous, concentric grooves commonly referred to as the “record-groove” pattern (Fig. 5). These grooves are generated by the mechanical ploughing action of the tool tip as it slides along the helical path. The groove spacing corresponds approximately to the layer pitch, and the ridge crests show evidence of material side flow and adhesive transfer. Such directional texture is mechanically weak in the transverse direction and may serve as initiation sites for fatigue cracks or corrosion pits.

In contrast, the IPF surface displays a distinctive honeycomb- or fish-scale-like pattern composed of numerous small, overlapping indentations (Fig. 6). This morphology is not produced by sliding friction but by repeated localized compression and material flow during each plunge event. The overlapping indents create a quasi-isotropic textured surface that resembles patterns produced by knurling, shot peening, or surface rolling. Such a surface texture is not merely an aesthetic feature; it also suggests the occurrence of surface severe plastic deformation and work hardening, which can enhance surface hardness and wear resistance [18].

The transition from record-groove to honeycomb texture represents a fundamental shift in the surface formation mechanism. In SPIF, the surface is generated by a cutting-like action where the tool ploughs through the material, removing or displacing material laterally and creating grooves with sharp ridges. The directionality of these grooves introduces anisotropy in surface properties, making the surface more susceptible to crack initiation perpendicular to the groove direction. In IPF, each indentation event compresses the material locally, causing radial material flow from the center of the indent outward. The overlap of successive indents creates a surface where the material has been uniformly work-hardened in multiple directions, resulting in a more isotropic surface condition. This distinction has important implications for the functional performance of the formed parts, as isotropic surfaces generally exhibit better resistance to directional fatigue crack propagation and more uniform corrosion behavior.

It is worth noting that Luo et al. [22] observed punch marks on the surfaces of parts formed by their incremental punching system, particularly when larger step sizes were used. They noted that smaller step sizes produced less visible punch marks and better surface finish. The present study extends this observation by providing quantitative surface roughness measurements and systematic morphological characterization, demonstrating that the surface texture produced by intermittent indentation is not merely a less severe version of the SPIF groove pattern, but a fundamentally different surface morphology with distinct characteristics and potential functional benefits.

4.3. Surface Roughness

The surface roughness measurements confirm the qualitative morphological observations. For the 60° cone, the average surface roughness R_a of the conventionally formed SPIF specimen was 1.116 μm under lubricated conditions. For the IPF specimen formed without lubricant, R_a was 0.611 μm ; with lubricant, R_a decreased further to 0.4 μm . The corresponding values of R_z followed the same trend. Thus, under comparable lubricated conditions, IPF reduced R_a by approximately 64% relative to conventional SPIF. The reduction in roughness is attributed to the elimination of continuous sliding friction and the replacement of ploughing grooves by smooth, localized indentations.

The beneficial effect of lubrication in IPF can be explained by the reduced adhesion and material transfer between the tool and the sheet during each plunge event. Even without lubricant, however, IPF already achieves a lower R_a than lubricated SPIF, indicating that the change in contact mechanics from sliding to indentation is the dominant factor in surface quality improvement. These results suggest that IPF may relax the stringent lubrication requirements often associated with conventional SPIF, thereby simplifying process implementation in industrial environments.

The surface roughness values obtained in this study can be contextualized within the broader ISF literature. Fracchia et al. [10] reported R_a values in the range of 1.5–3.5 μm for SPIF of AA5052, depending on process parameters. Cao et al. [12] measured R_a values of 0.8–2.0 μm for SPIF of AA5052 with various lubricants. The R_a value of 1.116 μm obtained for lubricated SPIF in this study falls within the expected range. The R_a value of 0.4 μm achieved by lubricated IPF represents a substantial

improvement that brings the surface quality closer to that achievable by conventional stamping processes, where Ra values of 0.3–0.8 μm are typical for aluminum alloy sheets.

From a mechanistic perspective, the surface roughness in SPIF is governed by two main factors: (i) the geometric roughness induced by the step-down between layers, which creates inter-layer ridges, and (ii) the friction-induced roughness from tool sliding, which creates within-layer grooves. In IPF, the within-layer grooves are eliminated because the tool does not slide along the surface. The remaining surface roughness is primarily determined by the geometry of the individual indentations and their overlap pattern. The indentation depth, which equals the layer pitch, and the in-plane feed increment jointly determine the indent overlap ratio and thus the resulting surface roughness. This implies that surface roughness in IPF can be further optimized by adjusting these parameters, similar to how step-down and feed rate are optimized in conventional SPIF.

4.4. Forming limit angle

The formability of IPF was evaluated using a variable-wall-angle funnel-shaped part, as illustrated in Fig. 8. The top opening had a wall angle of 45° , and the bottom region approached 90° . This geometry enables a single test to probe a continuous range of forming angles and identify the maximum angle reached before fracture. Identical geometries were formed by both conventional SPIF and IPF for direct comparison.

Figure 9 shows the formed parts after the limit-angle tests, and Fig. 10 summarizes the maximum forming angles attained. The conventional SPIF part fractured at a wall angle of 79° after reaching a forming height of 40 mm. The IPF part fractured at a wall angle of 80° with a forming height of 42 mm. Although the difference is modest, IPF consistently achieved a slightly higher forming limit angle. The marginal improvement may be attributed to the intermittent deformation mode, which allows short periods of stress relaxation and localized heat dissipation between successive plunge cycles, thereby delaying the onset of ductile fracture [19, 20].

The maximum forming angle of 80 degrees obtained for IPF on AA5754-O is comparable to values reported in the literature for SPIF of aluminum alloys. Jeswiet et al. [1] summarized maximum forming angles for various materials in SPIF, reporting values of 65–75 degrees for AA3003-O and 70–80 degrees for AA5754-O depending on process parameters. Hussain et al. [26] reported a maximum forming angle of approximately 76 degrees for AA2024-O in SPIF. The slightly higher forming limit observed for IPF in this study is consistent with the general understanding that deformation modes involving periodic unloading can enhance formability by allowing stress redistribution and strain rate effects. This phenomenon has been observed in other forming processes such as incremental forming with ultrasonic assistance [27] and pulsating hydroforming [28], where intermittent deformation has been shown to improve formability compared to continuous loading.

In the incremental punching system of Luo et al. [22], the maximum forming angle for SPCC steel (1 mm thick) was found to be approximately 63 degrees, which is comparable to the value of 65 degrees

reported in the literature for conventional SPIF of similar material. This suggests that the intermittent deformation mode does not impair formability relative to continuous SPIF. The present study extends this finding to aluminum alloy AA5754-O and further demonstrates a slight improvement in forming limit, which may be attributed to the different material properties and the specific process parameters used.

From a deformation mechanics perspective, the slight improvement in formability can be explained by several factors. First, the intermittent contact in IPF allows for elastic stress recovery between successive plunge events, reducing the accumulation of through-thickness shear strain that is a primary driver of fracture in SPIF [29]. Second, the absence of continuous sliding reduces frictional heating, which can cause localized softening and premature thinning in SPIF. Third, the predominantly compressive nature of the indentation deformation in IPF may promote more favorable stress states compared to the combined stretching-shearing mode in SPIF, potentially delaying the onset of tensile instability. However, further experimental and numerical studies are needed to fully elucidate these mechanisms.

5. Conclusion

This paper has introduced Incremental Plunge Forming (IPF), a die-less sheet metal forming process in which a ball-end tool intermittently plunges into and retracts from the sheet along a programmed trajectory. The present study has focused on the surface quality and formability aspects of the intermittent deformation mode, providing the first systematic comparison with conventional SPIF. The feasibility, geometric accuracy, surface integrity, and formability of IPF have been experimentally investigated using AA5754-O aluminum alloy sheets. The following conclusions can be drawn:

(1) IPF is capable of successfully forming complex sheet metal geometries, including shallow domes, 45 degree and 60 degree cones, and variable-wall-angle parts, without dedicated dies. The formed parts exhibit satisfactory geometric accuracy and smooth sidewall profiles. The implementation on a standard CNC milling machine demonstrates the accessibility of the process without requiring specialized equipment.

(2) The surface morphology of IPF-formed parts is fundamentally different from that of SPIF-formed parts. IPF produces a quasi-isotropic honeycomb-like texture rather than the directional record-groove pattern typical of SPIF. This change in morphology indicates a transition from sliding-dominated to indentation-dominated deformation, which has important implications for surface functional properties such as fatigue resistance and corrosion behavior.

(3) IPF substantially improves surface roughness. For 60 degree cones formed under lubricated conditions, the average surface roughness R_a was reduced from $1.116\text{ }\mu\text{m}$ (SPIF) to $0.4\text{ }\mu\text{m}$ (IPF), corresponding to a reduction of approximately 64%. Even without lubricant, IPF achieved a lower R_a ($0.611\text{ }\mu\text{m}$) than lubricated SPIF, indicating that the change in contact mechanics is the dominant factor in surface quality improvement.

(4) The forming limit angle of IPF (80 degrees) is slightly higher than that of conventional SPIF (79 degrees), suggesting that the intermittent deformation mode does not impair – and may marginally improve – formability. This is attributed to stress relaxation, reduced frictional heating, and more favorable deformation mechanics during intermittent indentation.

(5) The transition from record-groove to honeycomb surface texture in IPF represents a shift from pure geometric forming toward simultaneous geometry-property control. The quasi-isotropic, work-hardened surface produced by IPF may offer additional benefits in terms of surface hardness and wear resistance, opening possibilities for functional surface engineering of lightweight sheet parts.

Declarations

Ethical Approval:

Not applicable.

Consent to Participate:

All authors agreed to participate in this research.

Consent to Publish:

All authors have read and agreed to the published version of the manuscript.

Competing Interests:

The authors declare no competing interests.

Funding:

This work was funded by the Open Project Program of Anhui Engineering Research Center of Low-carbon Metallurgy and Process Control (Anhui University of Technology) [AHERC-LP-ZD24-03].

Author's Contributions:

Presentation of the original ideas and original paper drafting, Huiting Wang; Participated in some experiments and data analysis, Xiaohui Shen, Xing Chen and Hongbo Pan.

Acknowledgements

The authors are indebted to Dr. Jinxiu Fang, Anhui University of Technology, for assistance in the English revision of this article.

Availability of data and materials:

Not applicable.

References

1. Jeswiet J, Micari F, Hirt G, Bramley A, Duflou J, Allwood J (2005) Asymmetric single point incremental forming of sheet metal. *CIRP Ann* 54(2):623–649
2. Emmens WC, van den Sebastiani G (2010) The technology of incremental sheet forming - A brief review of the history. *J Mater Process Technol* 210(8):981–997
3. Duflou JR, Callebaut B, Verbert J, De Baerdemaeker H (2007) Laser assisted incremental forming: Formability and accuracy improvement. *CIRP Ann* 56(1):273–276
4. Behera AK, de Sousa RA, Ingarao G, Oleksik V (2017) Single point incremental forming: An assessment of the progress and future trends. *Int J Adv Manuf Technol* 81(1–4):703–725
5. Matsubara S (1986) A computer numerically controlled dieless incremental forming of a sheet metal. *Proc Inst Mech Eng B* 200(3):165–169
6. Jackson K, Allwood J (2009) The mechanics of incremental sheet forming. *J Mater Process Technol* 209(3):1158–1174
7. Eyckens P, Belkassam C, Henrard C, Gu J, Sol H, Habraken AM et al (2010) Strain evolution in the single point incremental forming process: Digital image correlation measurement and finite element prediction. *Int J Mater Form* 3(S1):55–71
8. Bambach M, Taleb-Araghi B, Hirt G (2011) Strategies to improve the geometric accuracy in asymmetric single point incremental forming. *Prod Eng Res Devel* 5(2):145–156
9. Li Y, Daniel WJT, Liu Z, Meehan PA, Kerr R (2019) Deformation mechanics in single-point incremental forming of locally-curved truncated conical parts. *Int J Mech Sci* 161–162:105064
10. Fracchia E, Bruschi S, Ghiotti A (2014) Influence of material microstructure and process parameters on surface roughness in single point incremental forming. *Procedia Eng* 81:2314–2319
11. Guo Y, He K, Yu Z (2018) The surface roughness in incremental sheet forming of AA5052 aluminum alloy. *Int J Adv Manuf Technol* 96(9–12):4437–4445
12. Cao T, Lu Y, Li H, Chen J (2015) Surface roughness in single point incremental forming of 5052 aluminum alloy. *J Manuf Process* 19:74–80
13. Bouzaiene H, Larbi MH, Tsoupis I, Gu J, Zribi M, Richard F et al (2015) Surface roughness and forming accuracy in incremental sheet forming of aluminium alloys. *Key Eng Mater* 651–653:1066–1071
14. Fiorentino A, Ceretti E, Attanasio A, Mazzoni L, Giardini C (2011) On the tool wear in friction stir welding and incremental forming. *Wear* 271(9–10):2426–2431
15. Gottmann A, Dietrich J, Bergweiler G, Bambach M, Hirt G, Loosen P et al (2011) Laser-assisted asymmetric incremental sheet forming of titanium sheet metal parts. *Prod Eng Res Devel* 5(3):263–

16. Durante M, Formisano A, Langella A (2011) Comparison between vertical and sloped wall geometries in single-point incremental forming. *Int J Mater Form* 4(2):177–180
17. Bahloul R, Arfa H, BelHadjSalah H (2014) A study on optimal design of process parameters in single point incremental forming of sheet metal by combining response surface methodology and genetic algorithm. *J Mech Sci Technol* 28(4):1449–1461
18. Mordyuk BN, Prokopenko GI (2007) Ultrasonic nanocrystal surface modification of low carbon steel: Fatigue performance and surface layer characteristics. *Mater Sci Eng A* 458(1–2):253–261
19. Young D, Jeswiet J (2004) Wall thickness variations in single-point incremental forming. *Proc Inst Mech Eng B* 218(11):1453–1459
20. Silva MB, Skjoedt M, Martins PAF, Bay N (2008) Revisiting the fundamentals of single point incremental forming by means of membrane analysis. *Int J Mach Tools Manuf* 48(1):73–83
21. Luo Y, He K, Du R (2010) A new sheet metal forming system based on the incremental punching, Part 1: Modeling and simulation. *Int J Adv Manuf Technol* 51(5–8):481–491
22. Luo Y, He K, Du R (2010) A new sheet metal forming system based on the incremental punching, Part 2: Machine building and experiment results. *Int J Adv Manuf Technol* 51(5–8):493–506
23. Durante M, Formisano A, Langella A (2010) Influence of tool rotation on surface roughness in incremental forming. *Key Eng Mater* 410:203–210
24. Fan G, Li Y, Chen J, Gao L (2010) Surface roughness of incremental sheet metal formed parts. *Adv Mater Res* 97–101:4095–4098
25. Ajajar M, Pascal JT, Bahloul R (2023) Recent advances in incremental sheet forming: A review of process variants and process parameters. *Int J Adv Manuf Technol* 128:1239–1273
26. Hussain G, Gao L, Hayat N, Dar NU (2010) The formability of annealed and pre-aged AA-2024 sheets in single-point incremental forming. *Int J Adv Manuf Technol* 46(5–8):543–549
27. Vahdati M, Mahdavinejad R, Amini S (2017) Investigation of the ultrasonic vibration effect in incremental sheet metal forming process. *Proc Inst Mech Eng B* 231(5):830–842
28. Loh-Mousavi M, Bakhshi-Jooybari M, Gorji A, Kasaei MM (2015) Hydrodynamic incremental forming of steel sheets. *Mater Manuf Process* 30(3):354–359
29. Malhotra R, Cao J, Ren F, Kiridena V, Cedric Xia Z, Reddy NV (2011) Improvement of geometric accuracy in incremental forming by using a multistep tool path strategy. *ASME J Manuf Sci Eng* 133(5):051019

Figures

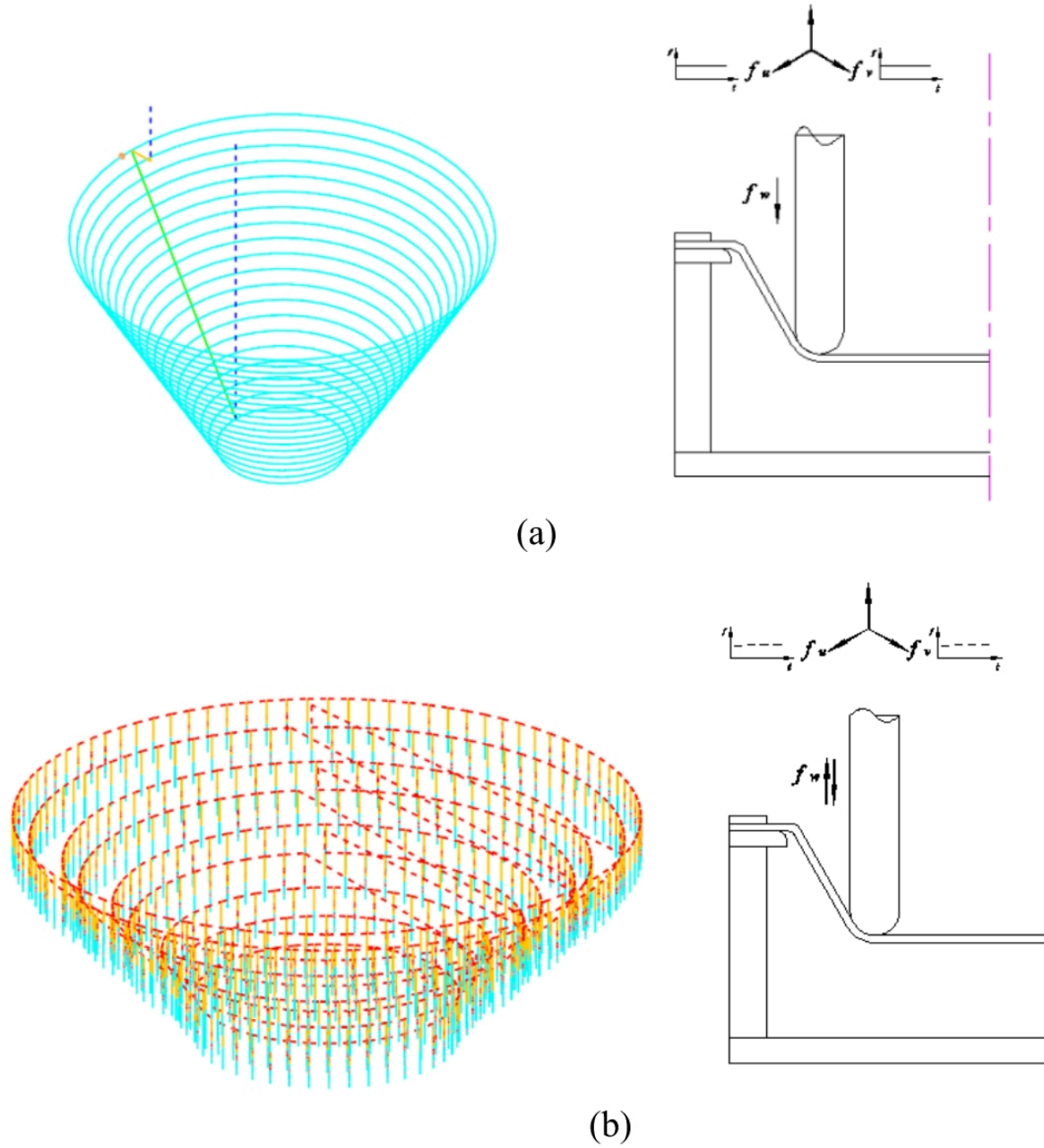


Figure 1

Schematic comparison of tool paths and forming principles: (a) conventional SPIF and (b) the proposed IPF.

(a) Conventional SPIF: continuous spiral tool path

(b) IPF: discrete plunge-retract tool path

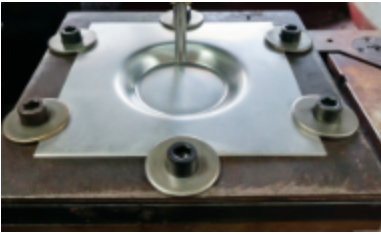


Figure 2

Experimental setup showing the ball-end forming tool and clamped AA5754 sheet blank on the CNC machine table.

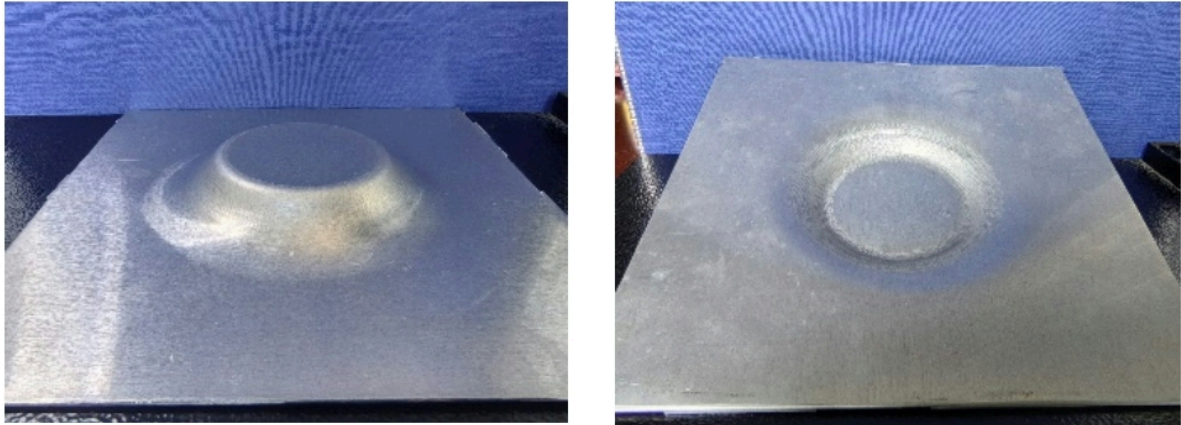


Figure 3

Part formed in the preliminary IPF feasibility test.

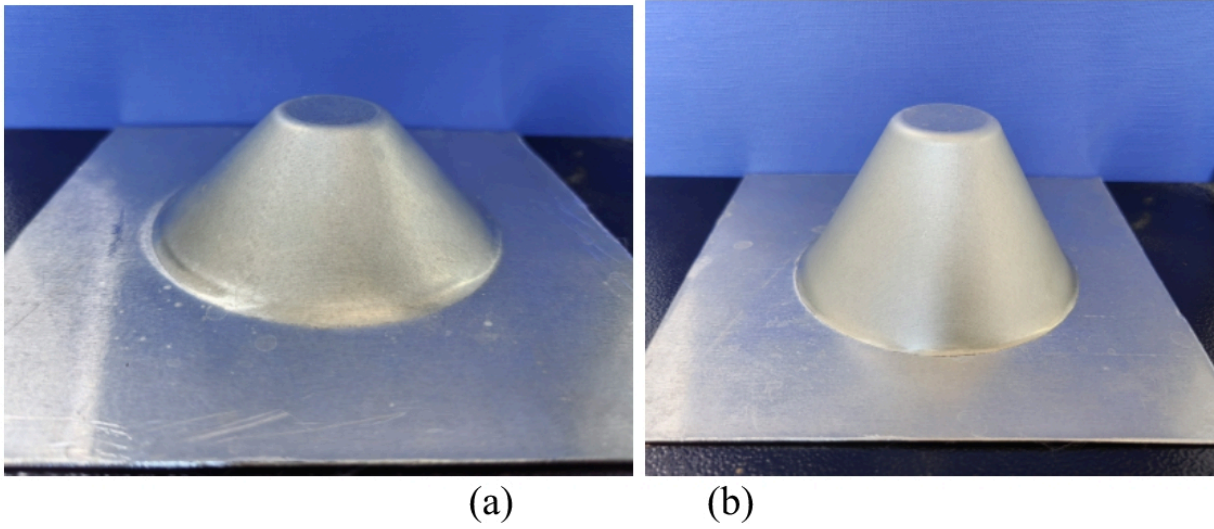


Figure 4

Conical parts formed by IPF: (a) 45° wall angle and (b) 60° wall angle.

(a) 45° cone (b) 60° cone

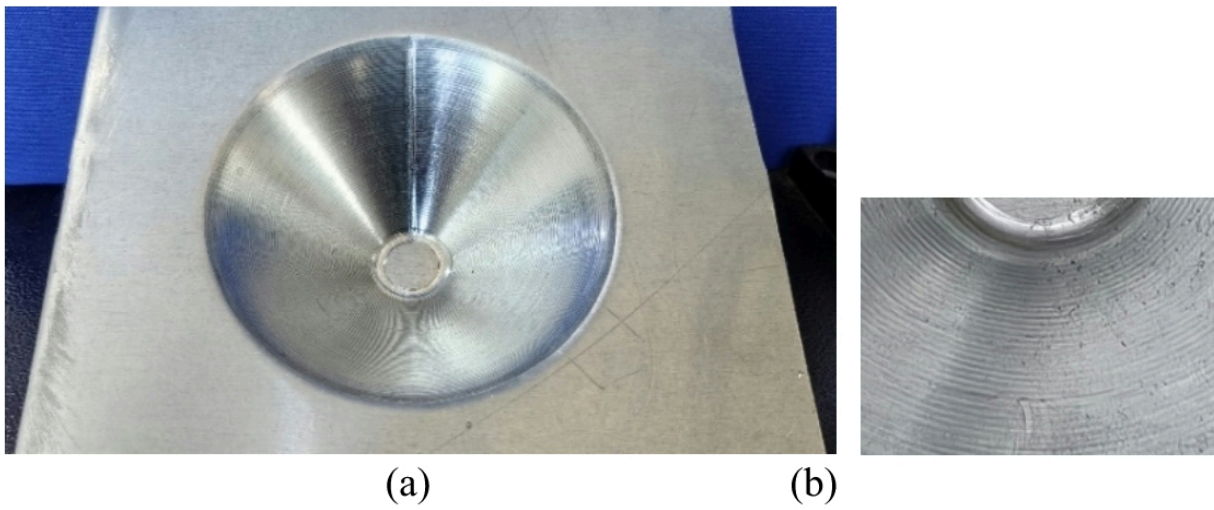


Figure 5

Typical surface morphology of a part formed by conventional SPIF, showing the directional “record-groove” pattern: (a) top view and (b) close-up view.

(a)Top view (b)Close-up view

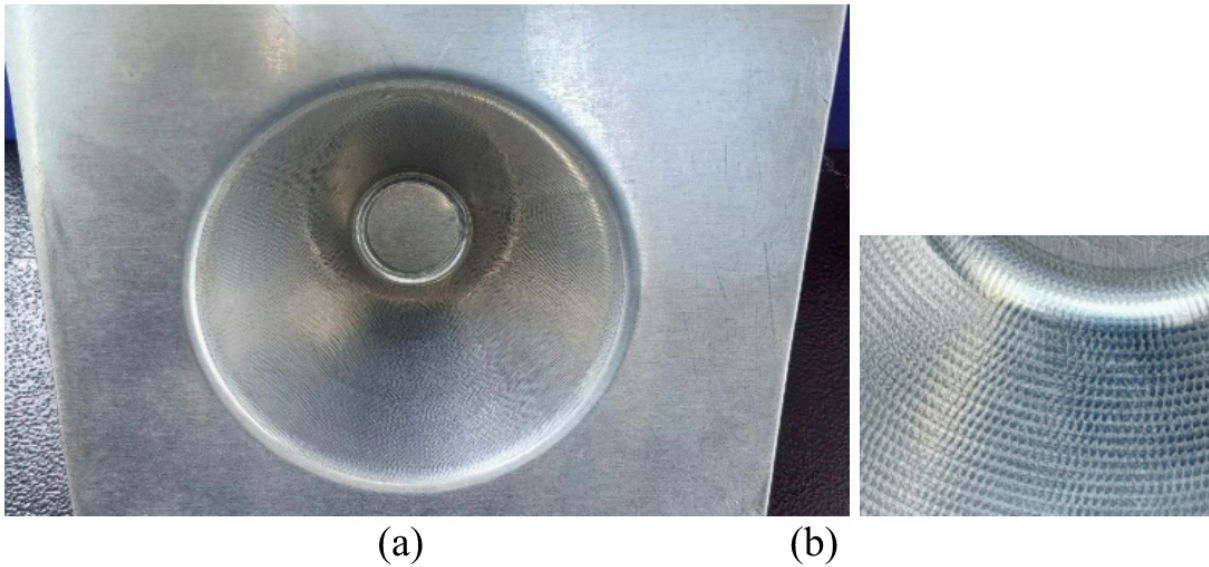


Figure 6

Surface morphology of a part formed by IPF, showing the honeycomb-like texture: (a) top view and (b) close-up view.

(a)Top view (b)Close-up view

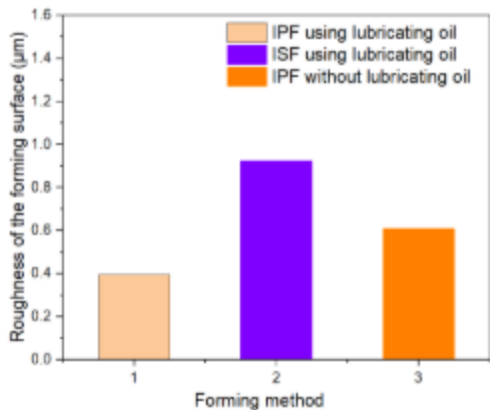


Figure 7

Surface roughness of 60° cones formed by SPIF and IPF.

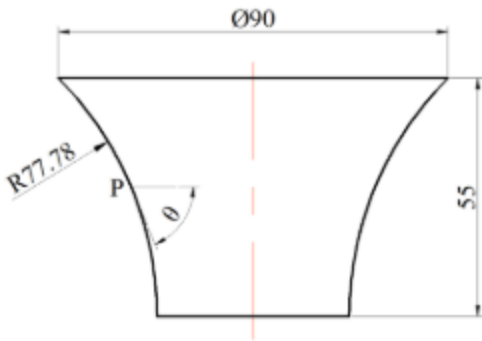


Figure 8

Geometry and dimensions of the variable-wall-angle part used for forming limit evaluation (units: mm).

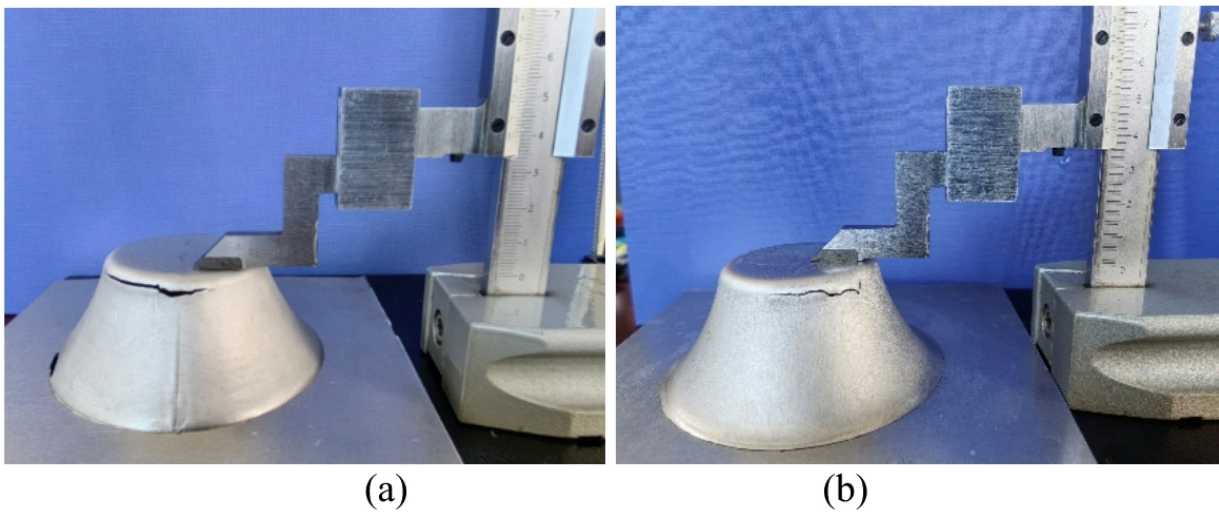


Figure 9

Variable-wall-angle parts formed by (a) conventional SPIF and (b) IPF, showing fracture locations at the limiting wall angles.

(a) Conventional SPIF (b) IPF

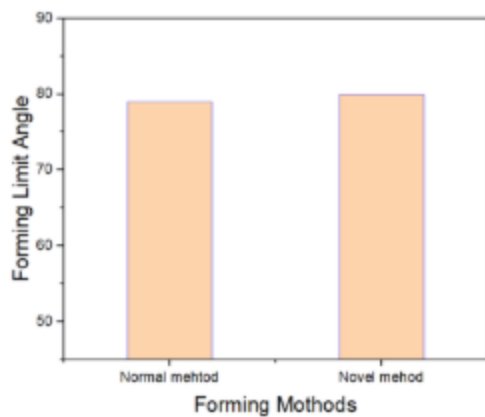


Figure 10

Comparison of maximum forming limit angles for conventional SPIF and IPF.