Experimental Investigation of Single Point Incremental Forming (SPIF) of Aluminium Alloy AA6061-T6

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***Abstract*— Single Point Incremental Forming (SPIF) has emerged as a flexible and cost-effective technique for manufacturing complex sheet metal components without the need for dedicated dies. This paper investigates the formability, deformation behaviour, and failure characteristics of Aluminium Alloy AA6061-T6 (1.5 mm thickness) under varying SPIF process conditions. Twenty experimental specimens were produced on a three-axis CNC vertical machining centre using a hemispherical forming tool, systematically varying step depth (0.2–4.5 mm), feed rate (500–1500 mm/min), spindle speed (800–1600 RPM), and part geometry (circular vs. square truncated profiles). Grid strain analysis using electrochemically etched circular patterns (2.5 mm nominal diameter) was employed to visualise and quantify deformation. Results indicate that step depth dominates surface quality, feed rate governs fracture risk, and elevated spindle speed induces unique failure modes including base punch-through and asymmetric circumferential tearing. Circular geometries demonstrated superior formability compared to square geometries due to uniform hoop stress distribution. An optimal process window was established at step depth ≤ 0.5 mm, feed rate 500–1000 mm/min, and spindle speed 1200 RPM for defect-free component production. The study provides practical guidelines for SPIF process design for AA6061-T6 in its peak-aged temper condition**

***Keywords:* Single Point Incremental Forming; SPIF; Aluminium Alloy AA6061-T6; Formability; Strain Distribution; Sheet Metal Forming; CNC Machining; Surface Defects; Grid Marking**

I. INTRODUCTION

Forming metals has been one of the key processes during the manufacturing of different products since the Industrial Revolution. As demands increase towards customized, low volume, and intricate geometries, there has been a requirement for flexible forming operations that remove the need for dies [1]. Sheet forming methods like deep drawing and stamping involve high costs associated with creating a mold and tooling, which make them economically viable for large-scale production only.

Single Point Incremental Forming (SPIF) is a die-less sheet metal forming method, where a hemispherical forming tool follows a series of contour paths on the fixed sheet metal blank to deform it into a desired shape incrementally. Patented by Leszak in 1967 [2], SPIF became feasible for implementation when Computer Numerical Control (CNC) machines were developed, and tool paths could be generated from computer models. The process utilizes standard three-axis CNC milling equipment, a sheet blank holding fixture, and a hemispherical tool to deform the sheet blank [3].

Aluminium Alloy 6061 in the Tempered Condition T6 (AA6061-T6) finds widespread use in industries like aerospace, automobile, and construction engineering because of its excellent mechanical and physical properties. While the T6 heat treatment process increases the mechanical properties, it limits the alloy's ductility (elongation at break ≈ 12%). This makes AA6061-T6 an unsuitable material for conventional incremental forming operations. Investigating the behavior of SPIF in AA6061-T6 and establishing its optimum process window is of significant industrial interest.

In this paper, a comprehensive experimental study on SPIF of AA6061-T6 has been conducted to examine the effects of step size, feed rate, spindle speed, and geometry on formability, surface finish, strain distribution, and failure modes. The goal is to establish a practical window within which AA6061-T6 can be successfully formed using SPIF.

II. MATERIALS AND METHODOLOGY

A. Material - AA6061-T6

For this experiment, Aluminium Alloy 6061-T6 was chosen as the material. It is part of the 6xxx family of aluminium alloys, where magnesium (Mg) and silicon (Si) act as the alloying elements that form the Mg_2Si precipitation hardening phase. The letter 'T6' represents the solution heat treatment with artificial aging to achieve maximum hardness. Plate blanks of 200 mm x 200 mm x 1.5 mm were cut precisely using shearing from the flat-rolled plates.

TABLE I: Mechanical Properties of AA6061-T6

Property	Value	Standard
Tensile Strength (UTS)	310 MPa	ASTM E8
Yield Strength (0.2%)	276 MPa	ASTM E8
Elongation at Break	12 %	ASTM E8
Young's Modulus	68.9 GPa	ASTM E111
Hardness (Brinell)	95 HB	ASTM E10
Density	2.70 g/cm³	ASTM B209
Poisson's Ratio	0.33	—

III. EXPERIMENTAL SETUP

A. SPIF Task Performed:

All SPIF trials were conducted using a three-axis CNC vertical milling machine (controller FANUC Series Oi-MD), equipped with axis travel of 600 mm (X), 400 mm (Y), and 450 mm (Z), spindle speeds ranging from 50 to 6000 RPM, and precision ±0.005 mm. Forming tools made from high-speed steel (M2, HSS grade, hardness 60–62 HRC), having fully hemispherical tips with surface roughness Ra < 0.4 µm. Three different tools diameters were used (6 mm, 10 mm, and 12 mm). Toolpaths were designed in CAD/CAM software and fed as G-code to the controller.

The blanks were mounted in a stiff fixture consisting of 20 mm steel base plate with a 150 mm x 150 mm hole at its center, with corresponding clamping frame with eight M10 bolts tightened with 25 N•m torque. Prior to each trial, the blank surface was coated with SAE 30 motor oil. Coordinate system (origin 0,0,0) was established at the upper surface center of each blank.

B. Process Parameters and Experimental Design

A total of four basic process variables were studied for their performance at three levels each, which are detailed in Table II. The two basic specimen shapes that were used are: (i) truncated cone geometry with a 45° wall angle and base diameter of 80 mm, and (ii) truncated square pyramid shape with a 45° wall angle and a base dimension of 80 mm x 80 mm.

TABLE II: Process Parameter Levels

Parameter	Level 1 (Low)	Level 2 (Medium)	Level 3 (High)
Step Depth (mm)	0.2	0.5	1.0 / 4.5
Feed Rate (mm/min)	500	1000	1500
Tool Diameter (mm)	6	10	12
Spindle Speed (RPM)	800	1200	1600

C. Grid Marking and Measurement Techniques

A circular grid pattern (2.5 mm nominal cell diameter) was electrochemically etched onto each blank surface prior to forming to enable post-forming strain analysis. High-resolution photographs of deformed grid patterns were analysed using ImageJ software (calibrated pixel-to-mm conversion) to determine major and minor principal strains from deformed ellipse dimensions. Sheet thickness was measured using an ultrasonic digital gauge (resolution 0.01 mm) along radial and circumferential paths. Surface roughness (Ra) was evaluated by a contact profilometer (Gaussian filter, 0.8 mm cut-off). Geometric accuracy was assessed by height gauge measurements compared against the nominal CAD profile.

IV. RESULTS AND DISCUSSION

A. Deformation Behavior and Strain Distribution

The analysis using the grids of the circular samples formed revealed the localized nature of SPIF. While grids in the formed wall areas were distorted in an ellipsoid shape, those in the flange areas remained unchanged in terms of geometry; they remained circular. Thus, this result confirmed the theoretical prediction of the localized nature of the strain field, and further revealed that plastic deformation occurred only within the immediate area of tool-contact.

The elongation of grid squares was noted in the circumferential direction, specifically within the mid-wall and upper-wall areas. As expected from the predictions of the sine rule, the increase in the strain gradient corresponded with the increase in wall angle. The measured thickness to initial thickness ratios (t/t_0) followed the relationship $t = t_0 \times \sin(90° - \alpha)$.

B. Effect of Step Depth on Surface Quality

tep depth emerged as the primary variable influencing surface quality. Specimens with a step depth of 0.5 mm had smooth walls without any fractures, wrinkles, or step marks, indicating an almost ideal combination of parameters. However, at 4.5 mm step depth, there were evident marks of the tool path, known as step-band marks, associated with each progressive pass, with increased surface roughness but without any complete fractures. These step marks would be unacceptable in most engineering applications, indicating that the step depth must be moderate for AA6061-T6.

The adverse influence of excessive step depth on surface quality is due to the larger volume of material subjected to plastic deformation per pass. This results in a higher force interaction between the tool and workpiece, causing greater thinning per pass and surface indentation.

C. Effect of Feed Rate on Fracture Behaviour

Feed rate was established as the controlling factor influencing fracture behaviour. Specimens created using a feed rate of 1500 mm/min always experienced circumferential (hoop-direction) fracturing at mid-to-upper wall levels. This failure mechanism is typical for AA6061-T6 formed using SPIF. The crack travels parallel to the shape of the toolpath contour since the highest tensile hoop strain surpasses the fracture strain of the T6 alloy.

High feed rate results in an increase in the magnitude of impulse-type contact loads experienced by the specimen per unit time, accelerating the strain generation rate without allowing sufficient strain hardening time to distribute deformation energy evenly. Necking is accelerated at the most strained area, which is generally the middle wall level with maximum accumulated toolpath strain. On the other hand, 500–1000 mm/min feed rates allow sufficient strain relaxation for adequate material flow and lubricant film stability without surface defects.

D. Effect of Spindle Speed on Failure Mode

Increasing spindle speed led to unique failure modes different from changes in step depth and feed rate. A completely base punch-through failure was observed in specimens created using high RPM. Thermal softening of the specimen due to frictional heating induced bending and contact stresses in the base region, resulting in a fracture failure. A high-RPM specimen displayed asymmetric circumferential tearing at the top of the wall. Unstable crack propagation was noted, implying non-uniform frictional heating of the toolpath contact perimeter.

Moderate tool rotation at 1200 RPM increases surface finish through contact polishing of the toolpath perimeter, but excessive RPM leads to thermal softening that destabilises the deformation zone and accelerates premature failure. Asymmetric failure mode further indicates the presence of process instability caused by high RPM.

E. Geometry Comparison: Circular vs. Square

A comparison between circular and square shapes showed improved formability for circular shapes compared to square geometries using the same processing parameters. The key difference is that circular geometry provides a uniform hoop stress throughout the forming trajectory, while square geometry causes stress concentration on corner areas and reduces stress on flat wall areas.

Wrinkling behaviour was more evident at the flange corners for square specimens compared to circular specimens. Square specimens also displayed higher surface degradation due to lubricant burning, oxidation spots, and base surface scarring compared to circular specimens. However, high-quality square specimens could be achieved using conservative processing parameter combinations, especially low step depths and moderate forming depth, indicating the possibility of SPIF of non-circular geometries using proper parameter settings.

F. Failure Analysis

Two major failure modes were observed among all specimens in the experiment:

(1) Circumferential Ductile Fracture: The main failure type involving cracking propagation in the circumferential direction along the toolpath contour. Fracture initiates when maximum principal tensile strain in the wall level surpasses the fracture strain of AA6061-T6. Fracture location depends on maximum accumulated strain, which usually occurs at mid-wall and upper-wall levels. Fractured specimens have irregularly torn surfaces, not clean shear lines, suggesting ductile tearing consistent with the material's moderate elongation capability under the T6 temper.

TABLE III: Summary of Key Experimental Results

Specimen Condition	Geometry	Outcome	Primary Observation
SD=0.5mm, FR=1000	Circular	Defect-free	Optimal: clean smooth wall surface
SD=4.5mm, FR=1000	Circular	Step marks	Prominent toolpath ridges; no fracture
SD=0.5mm, FR=1500	Circular	Mid-wall crack	Circumferential hoop fracture
High RPM (elevated)	Circular	Punch-through	Base fracture; frictional heat-induced
High RPM (elevated)	Circular	Asymm. tear	Uneven circumferential fracture
Moderate params	Square	Corner wrinkle	Stress concentration at corners
PCD32, SD5, Low feed	Circular	Best quality	Exceptional surface finish; no defects

V. CONCLUSIONS

- SPIF can be applied to AA6061-T6 under optimal parameters. Perfect truncated cones with smooth surfaces were created under step depths ≤ 0.5 mm, feed rates between 500–1000 mm/min, and a spindle speed of 1200 RPM.
- Step depth is the key factor that influences surface finish. As step depth increased from 0.5 mm to 4.5 mm, unacceptable tool path marks were evident even without full fracture.
- Feed rate is the key factor that influences fracture. Feed rates exceeding 1000 mm/min caused continuous hoop fracture midway through the upper wall height.
- Increased spindle speed brings in new types of fracture. High RPM caused thermal softening, resulting in punching base fractures and circumferential fracture tearing, which differ from step depth and feed rate fractures.
- Circles exhibit better formability than squares because of more evenly distributed hoop stresses. Squares experience early wrinkling and surface deterioration around corners.
- The best processing range using a 10 mm tool diameter was found to be: step depth of 0.5 mm, feed rates of 500–1000 mm/min, and spindle speed of 1200 RPM.
- Grid strain analysis proved that SPIF strains are localized only within the tool engagement zone, proving the sine rule approximation and verifying the use of electrochemical grid marking for strain evaluation in AA6061-T6.

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