Effect of Process Parameters on Single Point Incremental Forming of AA5052-H32 Aluminum Alloy

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Abstract— **Single Point Incremental Forming (SPIF) is a flexible, die-less sheet metal forming process well-suited for rapid prototyping and small-batch production of complex geometries. This paper presents an experimental investigation of SPIF applied to AA5052-H32 aluminum alloy sheet, examining the effects of step depth, feed rate, and tool diameter on formability, deformation behavior, strain distribution, thickness variation, and surface quality. Experiments were conducted on both circular and square geometries to provide a comparative understanding of geometry-dependent forming behavior. Results demonstrate that step depth is the dominant parameter governing formability and surface quality, while feed rate critically influences surface roughness and material flow stability. Circular geometries exhibited more uniform strain distribution and superior formability limits compared to square geometries. Thickness distribution analysis confirmed the sine law of incremental forming. A process window identifying safe forming conditions was established. The findings offer practical guidelines for SPIF of AA5052-H32 in marine, automotive, and aerospace applications.**

Keywords: **Single Point Incremental Forming; AA5052-H32; Step Depth; Feed Rate; Formability; Surface Defects; Aluminum Alloy.**

I. INTRODUCTION

Metal forming is a cornerstone of modern manufacturing, enabling the production of complex shapes from sheet metal with high material efficiency. Single Point Incremental Forming (SPIF) represents an innovative departure from conventional stamping by eliminating the need for dedicated dies, instead using a computer-numerically controlled (CNC) forming tool that traverses a programmed helical toolpath to progressively deform a clamped sheet blank into the desired geometry [1].

SPIF first appeared as a patent concept by Lezak in 1967, but its practical realization was delayed until CNC systems and associated software matured sufficiently to enable precise tool motion control [2]. Since then, SPIF has attracted considerable research interest owing to its ability to achieve forming limits significantly beyond those attainable in conventional deep drawing, attributable to the dominant through-thickness shear deformation mechanism that differs fundamentally from biaxial stretching [3].

AA5052-H32 is a strain-hardened Al-Mg alloy in the quarter-hard (H32) temper, widely employed in marine vessel components, fuel tanks, automotive panel skins, and pressure vessels due to its excellent corrosion resistance in salt-water environments and good baseline formability. Its moderate yield strength (193 MPa),

TABLE I. MECHANICAL PROPERTIES OF AA5052-H32

Property	Value	Unit
Ultimate Tensile Strength	228	MPa
Yield Strength (0.2%)	193	MPa
Elongation at Break	12–15	%
Vickers Hardness	60	HV
Young's Modulus	70.3	GPa
Poisson's Ratio	0.33	—
Density	2.68	g/cm^3
Strain Hardening Exp. (n)	0.13	—
Mean r-value	0.77	—

II. MATERIALS AND METHODOLOGY

A. Material: AA5052-H32

AA5052-H32 is a non-heat-treatable wrought Al-Mg alloy (5xxx series) in the quarter-hard temper condition. The H32 designation indicates strain hardening to the H3x level followed by a low-temperature stabilization treatment. This temper provides a favorable balance of gauge. Dimensional accuracy was assessed using a Zeiss Contura 3D CMM (Renishaw SP25M scanning probe; ±0.005 mm). Grid strain analysis employed 2 × 2 mm electrochemical grid etching with ASAME software for principal strain computation. Vickers hardness (HV0.5) was measured using a Shimadzu HMV-G21DT tester.

III. EXPERIMENTAL SETUP

A. 3-axis CNC

A 3-axis CNC vertical machining centre (FANUC 0i-MF controller; 600 × 400 × 500 mm travel; ±0.01 mm positioning accuracy) was adapted as the SPIF platform. Hemispherical HSS and tungsten carbide forming tools of diameters 6 mm, 10 mm, and 12 mm were employed. A purpose-designed mild steel fixture with a 230 × 230 mm aperture clamped blanks at 45 N•m torque. Contour-following helical toolpaths were generated in Mastercam® and loaded via DNC interface. Mineral oil (ISO VG 46) was applied as lubricant, replenished every 15 minutes.

B. Process Parameters and DOE

Four primary process parameters were varied at three levels each following a Taguchi L-9 orthogonal array (Table II). Experiments were conducted at room temperature (23 ± 2°C) on 1.5 mm thick blanks for the primary DOE, with supplementary trials at 1.0 mm and 2.0 mm.

TABLE II. SPIF PROCESS PARAMETERS AND LEVELS

Parameter	Level 1	Level 2	Level 3	Unit
Step Depth (Δz)	0.2	0.5	1.0	mm
Feed Rate (f)	200	500	800	mm/min
Tool Diameter (D)	6	10	12	mm
Spindle Speed (N)	500	1000	1500	RPM

C. Measurement Techniques

Surface roughness (Ra) was measured using a Mitutoyo Surftest SJ-210 contact profilometer (ISO 4287). Wall thickness was measured at 24 equidistant points using an Olympus ultrasonic extended elongation (12-15%), and progressive work-hardening behavior make it an attractive candidate for SPIF applications where large incremental plastic strains are demanded [4].

Despite growing literature on SPIF, systematic experimental investigations comparing circular and square geometries for AA5052-H32—and explicitly characterizing the process window boundaries for step depth and feed rate—remain limited. This paper addresses these gaps through a structured experimental program using a Taguchi L-9 design of experiments and presents quantitative results on deformation behavior, strain distribution, thickness variation, surface defects,

IV. RESULTS AND DISCUSSION

A. Deformation Behavior

Circular specimens exhibited uniform radial strain distribution consistent with axisymmetric deformation, with smooth metal flow progressing from the flange toward the formed wall governed by the through-thickness shear mechanism. The Mg-Cr solid-solution strengthening of AA5052-H32 facilitated progressive work hardening across the forming zone without impeding plastic flow.

Square specimens exhibited markedly more complex deformation. Corner regions experienced concentrated biaxial tensile stresses, while straight-wall sections followed a plane-strain condition. This non-uniform stress state produced differential thinning, with corner zones showing significantly greater thickness reduction than straight walls. The strain hardening exponent n = 0.13 provided a moderate mitigating effect by redistributing deformation away from the most highly strained zones.

B. Thickness Variation

Maximum thinning consistently occurred at the tool nose contact radius. Successful specimens recorded thinning of 15–25% at this critical zone, within acceptable structural limits. The theoretical sine law ($t_f = t_0 \times \sin(90° - \theta)$) provided a reliable baseline, with experimental measurements closely following the predicted distribution. Table III summarizes the Thickness Thinning Ratio (TTR) at critical locations.

TABLE III. THICKNESS THINNING RATIO (TTR) AT CRITICAL LOCATIONS

Location	TTR Circular	TTR Square

	(%)	(%)
Component Base	2–5	3–6
Mid-Wall	8–15	10–18
Tool Radius Zone	15–25	18–30
Corner Regions	N/A	20–32
Flange (Thickening)	+3–8	+4–10

Failed specimens exhibited thinning exceeding 32–38% at fracture sites, confirming ductile tensile fracture as the dominant failure mechanism. Flange thickening resulted from compressive circumferential (hoop) strains.

Formability and strength: elevated yield strength relative to the annealed (O) condition with sufficient ductility for SPIF. Sheet blanks (250 mm × 250 mm) were procured in 1.0 mm, 1.5 mm, and 2.0 mm thicknesses conforming to ASTM B209. Table I summarizes the key mechanical properties.

C. Effect of Step Depth

Step depth was the most influential process parameter. At Δz = 0.2 mm, AA5052-H32 underwent gradual strain accumulation enabling progressive work hardening; resulting components showed smooth wall profiles, well-defined flanges, and Ra < 1.0 µm. Increasing Δz to 0.5 mm produced minor surface marks and slight cup ovality, while the alloy's moderate strain-hardening capacity (n = 0.13) partially compensated for the increased per-pass strain, yielding a wider acceptable forming window than higher-strength alloys.

At Δz = 1.0 mm, specimens failed through tearing at the tool contact radius or flange wrinkling. Square specimens proved more sensitive to step depth due to corner stress concentrations: a Δz = 0.5 mm that produced acceptable circular components caused visible corner cracking in square specimens when combined with high feed rates. Table IV summarizes the effects.

TABLE IV. EFFECT OF STEP DEPTH ON FORMING OUTCOME

Δz (mm)	Ra (µm)	Max Thin. (%)	Circular	Square
0.2	<1.0	15–18	Defect-free	Defect-free
0.5	1.0–1.6	18–25	Minor marks	Corner marks
1.0	>2.0	30–38	Tearing/Wrinkle	Corner cracking

D. Effect of Feed Rate

At f = 200 mm/min, adequate stress relaxation time permitted uniform plastic flow, smooth surfaces with consistent wall thickness, and effective lubrication retention at the tool-workpiece interface. This was particularly beneficial for AA5052-H32, which has moderate susceptibility to galling under dry contact.

At f = 500 mm/min, competing effects were observed: strain-rate hardening temporarily improved necking resistance, but increased frictional heating reduced lubrication effectiveness. The optimal feed rate was determined to be 500 mm/min, producing Ra = 1.0–1.6 µm with forming times approximately 60% shorter than the lowest speed, consistent with prior GRA optimization results for AA5052 pyramid SPIF.

At f = 800 mm/min, characteristic serrated or toothed edge defects appeared at the component rim, attributed to unstable metal flow, vibration effects, and reduced lubrication effectiveness. These defects were consistent across all step depths tested at this feed rate.

E. Surface Defects Analysis

Four primary defect categories were identified and characterized:

F. Geometry Comparison: Circular vs. Square

Circular components demonstrated axisymmetric deformation with predictable material flow, well-defined sine-law-governed thinning, and maximum forming angles up to 70° at optimal parameters (Δz = 0.2–0.5 mm, f = 500 mm/min, D = 10 mm), exceeding the ~63° typical for AA6061-T6 under equivalent conditions.

Square components required geometry-specific parameter optimization due to competing deformation modes: equibiaxial stretching at corners versus drawing-dominated deformation along straight walls. Maximum forming angle was limited to approximately 62° before corner cracking. Table V provides a comprehensive comparison.

G. Failure Analysis and Process Window

Failure analysis classified observed failures into three categories:

• Ductile tearing (most frequent): Initiated at the tool contact radius zone under combined bending and tensile overload. The local thinning threshold before fracture was approximately 32–38% for AA5052-H32. Contributing factors included Δz = 1.0 mm, f = 800 mm/min, and insufficient lubrication.
• Wrinkling-induced collapse: Occurred when blank holder force was insufficient to restrain the flange. More prevalent in thin blanks at high D/t ratios. In square specimens, geometry mismatch reduced blank holder effectiveness at straight-wall sections.
• Edge cracking (serrated rim): Associated with f = 800 mm/min regardless of step depth, attributed to unstable metal flow and tool vibration. Requires additional.
• Wrinkling: Compressive instability in the flange region caused by circumferential stresses exceeding the critical buckling stress. More prevalent in AA5052-H32 than in higher-yield-strength alloys owing to its lower yield strength (193 MPa). Severity increased with blank diameter-to-thickness ratio (D/t).
• Tearing: Tensile fracture at the tool nose radius zone where bending, unbending, and tensile wall stresses coexist. Tear surfaces exhibited ductile dimple morphology consistent with tensile overload. Strongly correlated with $\Delta z \geq 1.0$ mm and $f \geq 800$ mm/min.
• Thinning: Localized excessive thickness reduction beyond the sine law prediction. A circumferential thinning band or groove was the characteristic visual indicator. Amplified by insufficient lubrication, high blank holder force, and large tool-to-sheet clearance.
• Surface Roughness: Influenced by die surface texture (honeycomb pattern transferred to blank), lubrication effectiveness, and forming speed. Roughness was higher on die-contact than on tool-contact surfaces; elevated feed rates promoted galling on the softer AA5052-H32 matrix (HV = 60).
A failure mode map was constructed identifying three distinct regions in the Δz–f parameter space (Table VI):

TABLE VI. FAILURE MODE MAP — PROCESS WINDOW FOR AA5052-H32 SPIF

Zone	Δz (mm)	f (mm/min)	Defect	Corrective Action
Safe Forming	≤0.5	≤500	None	Maintain params.
Wrinkling	0.2–0.5	200–500	Flange wrinkle	Increase BHF
Tearing	1.0	500–800	Ductile tear	Reduce Δz to ≤0.5
Edge Cracking	Any	800	Serrated rim	Reduce f to ≤500
Combined Fail.	1.0	800	Tear + cracking	Reduce Δz and f

V. CONCLUSIONS

This study experimentally investigated SPIF of AA5052-H32 aluminum alloy for circular and square geometries under varying step depth, feed rate, tool diameter, and spindle speed. The following conclusions were drawn:
• Step depth is the dominant parameter: Δz = 0.2 mm yields defect-free components with Ra < 1.0 µm; Δz = 1.0 mm causes tearing and wrinkling. Square geometries are more sensitive to step depth due to corner stress concentrations.
• Optimal feed rate is 500 mm/min: This balances surface quality (Ra = 1.0–1.6 µm) with productivity (~60% shorter cycle than f = 200 mm/min). Feed rates of 800 mm/min consistently produce serrated edge defects.
• Circular geometries outperform square: Maximum forming angles of 70° versus 62°, more uniform strain distribution, and higher parameter tolerance were observed for circular profiles.
• The sine law governs thickness distribution: Maximum thinning (15–25%) occurs at the tool contact radius; fracture initiates when local thinning exceeds 32–38%.
• A process window was established: Safe forming conditions are $\Delta z \leq 0.5$ mm and $f \leq 500$ mm/min for 1.5 mm AA5052-H32 sheet with a 10 mm hemispherical tool.
Future work should include FEM simulation for springback prediction and toolpath compensation, variable blank holder force strategies, warm incremental forming to extend the process window, and machine learning-based multi-response optimization integrating Ra, Φ_{max}, thickness uniformity, and dimensional deviation.

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