

Research Article

Influences of Vibration Parameters on Formability of 1060 Aluminum Sheet Processed by Ultrasonic Vibration-Assisted Single Point Incremental Forming

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With increasing design complexities of thin-walled parts, the requirement of enhanced formability has impeded the development of the single point incremental forming (SPIF) process. In the present research, the ultrasonic vibration-assisted single point incremental forming (UV-SPIF) method was introduced to increase the formability of sheet metals. AL1060 aluminum alloy was adopted as the experimental material, and a truncated cone part was considered as the research object. The simulation model of UV-SPIF was established to analyze the distribution of plastic strains in the formed part. A forming angle was selected as the measuring index of formability of the aluminum sheet, and the influences of different vibration parameters on formability were evaluated. An experimental platform was devised to verify the accuracy of the obtained simulation results. It was found that ultrasonic vibration effectively improved the forming limit of the sheet. When the amplitude was 6 μ m and the frequency was 25 kHz, the sheet yielded the best formability with the largest forming angle of 67 degrees.

1. Introduction

Single point incremental forming (SPIF) is a dieless and unconstrained forming method to process sheet metals with local dynamic loading and uneven deformation. It is a flexible, rapid manufacturing technology and requires no special fixtures [1]. SPIF possesses the advantages of high flexibility, low forming force, and short design cycle; thus, it can effectively eliminate common problems, such as the long design period, large site occupation, high development cost, and poor flexibility, of the traditional stamping process [2].

In SPIF, due to excessive localized stresses, sheet metals are susceptible to destabilization, wrinkling, and cracking; hence, poor forming efficiency and surface quality have restricted its industrial applications [3].

Shrivastava and Tandon [4] analyzed the microstructural features and the modes of strains in different stages of SPIF through electron backscattered diffraction (EBSD) and X-ray diffraction (XRD) methods and identified the reasons for typical sheet metal failure under the biaxial strain mode.

In order to produce sheet metals with improved formability, multifarious forming methods, such as double-sided incremental forming [5], electromagnetic incremental forming [6, 7], hot incremental forming [8], and other compound processes [9, 10], have previously been employed.

In recent years, ultrasonic vibration has been adopted in several plastic forming processes, including pipe drawing and volume forming [11, 12], and this new technology is termed the ultrasonic vibration-assisted single point incremental forming process (UV-SPIF). Zhou et al. [13] applied UV-SPIF to produce sheet metals with improved surface quality and reduced distortion. Amini et al. [14] employed UV-SPIF to execute straight groove forming on a 1050 aluminum sheet. Li et al. [15] also used UV-SPIF and noticed a significant improvement in forming quality. Obikawa and Hayashi [16] applied UV-SPIF to aluminum alloy, steel, and titanium sheets and reported considerable improvements in both geometric accuracies and forming limits of the experimental parts. Li et al. [17] studied the deformation mechanism of sheet metals under UV-SPIF through finite element simulations.

Scholars have carried out a lot of effective work in the field of compound SPIF. A lot of research has been performed on UV-SPIF, focusing on forming force. In this paper, ultrasonic vibration was applied to the forming tool head in order to change the continuous extrusion contact between the tool head and an AL1060 aluminum alloy sheet. The influences of different vibration parameters on formability were investigated through simulations and experiments.

2. Principle of UV-SPIF

The conventional SPIF process works based on the principle of layered manufacturing. The metal sheet is formed layer by layer by the tool head along the predetermined track, and the forming trajectory is controlled by using a numerical control (NC) program (Figure 1). The sheet is first clamped on the worktable of the NC machine using the upper and the lower platens. The tool head extrudes the sheet layer by layer at a feed rate of V_1 and at a rotational speed of V_2 . In Figure 1, D is the diameter of the forming tool, α is the wall angle, Δz is the layer spacing, h is the initial sheet thickness, and h_0 is the thickness of the final shape. In UV-SPIF (Figure 2), ultrasonic vibration is generally applied to the tool head of the conventional SPIF system.

In UV-SPIF, the tool head performs a periodic reciprocating motion along the vertical direction (Figure 3). Ultrasonic vibration applied to the tool head is harmonic vibration of frequency f and amplitude A. The tool head selects the point o as the starting point and executes a sinusoidal motion (one and a half cycles) in the direction of the axis (Figure 4: abscissa t represents the time, ordinate H signifies the vibration displacement, and A denotes the amplitude). The tool head makes a contact with the sheet at point o and moves down during processing. After reaching the maximum amplitude, the tool head starts to move upwards and remains in contact with the sheet until point *a*. When the tool head attains the maximum amplitude, it again begins to move down and recontacts with the sheet at point b. The tool head repeats its motion in the oa segment after completing one cycle. It is noticeable that the tool head is separated from the sheet in the ab section, which covers half of the entire cycle.

The introduction of ultrasonic vibration makes the forming mechanism of SPIF more complex. The continuous squeezing contact between the tool head and the metal sheet is replaced by intermittent contact of high frequency. When the tool head becomes detached from the sheet, lubricant fluid flows into the gap to improve the frictional effect. Therefore, UV-SPIF causes significant enhancements in lattice dislocation density and the dislocation ratio through grain refinement and improves the plastic deformation of the sheet to yield better formability.

3. Finite Element Simulation of UV-SPIF

3.1. Finite Element Modeling of Incremental Forming of Frustum Part. An AL1060 aluminum alloy sheet of dimensions $140 \text{ mm} \times 140 \text{ mm}$ and initial thickness 1 mm was selected as the experimental material. An S4R four-node

reduced integral shell element was used to divide the mesh model, and the mesh size was set to $1 \text{ mm} \times 1 \text{ mm}$. The definition parameters of mesh generation, material model selection, and contact and boundary conditions are depicted in Table 1. In addition, Table 2 presents the stress-strain properties of the 1060 aluminum. The outer and the inner radii of each fixture platen (upper and lower) were 70 mm and 55 mm, respectively. The forming tool and the fixture platens were both considered to be rigid bodies. The Coulomb friction was selected as the friction type because the tangential force was smaller than both axial and radial forces. The friction coefficient between the sheet and tool head was set to 0.1, whereas the value between the sheet and the fixture platens was 0.2. The translational and the rotational movements of the fixture platens were constrained in all directions, and the sheet was tightened by the fixture platens. The finite element model of the proposed UV-SPIF system is illustrated in Figure 5.

The axial ultrasonic vibration motion applied to the tool head makes the UV-SPIF forming trajectory more complex. Each layer trajectory of the tool head for forming a truncated cone was circular. The periodic amplitudes in the *X* and *Y* directions were expressed in the Fourier series:

$$a = A_0 + \sum_{n=1}^{N} \left[A_n \cos n\omega \left(t - t_0 \right) + B_n \sin n\omega \left(t - t_0 \right) \right], \quad (1)$$

where A_0 is the initial amplitude, N is the number of the Fourier series terms, ω denotes the round frequency (rad/s), and t_0 is the initial time. The displacements of the tool head in the X and Y directions were also realized by the Fourier series:

$$X = R \cos 2\pi t,$$

$$Y = R \sin 2\pi t.$$
(2)

where *R* is the radius of each circular trajectory and *t* is the forming time in each trajectory.

In UV-SPIF, ultrasonic vibration causes the tool head to undergo a short displacement-high-frequency motion relative to the sheet. Ultrasonic vibration that occurred in the Z direction of the tool head was expressed by equation (3). The ultrasonic vibration simulation was executed in ABAQUS according to the following order of operations: Interaction– tools–amplitude–create-periodic. The simulation interface for ultrasonic vibration is displayed in Figure 6:

$$Z = A \sin[2\pi f(t)], \qquad (3)$$

where *A* and *f* are the respective amplitude and frequency of ultrasonic vibration. When f = 20 kHz and A = 0.03 mm, the value of circular frequency $(2\pi f(t))$ was calculated as 125600.

3.2. Thinning Analysis of UV-SPIF Area. The stress map of the 1060 aluminum sheet (in ABAQUS) is presented in Figure 7. The molded part is half-viewed, and the node path through the cutaway is exhibited in Figure 8.

The variation in sheet thickness along the cutaway junction path is illustrated in Figure 9. It is noticeable that



FIGURE 1: Principle of conventional SPIF.







FIGURE 3: Forming track.

the sheet broke when it was thinned from 1 mm to 0.3 mm. The thinning of the sheet was nonlinear, and the center position of the side wall of the truncated cone was found to be the thinnest area. The thinning rate decreased from the center to the top and to the bottom of the side wall; as forming depth increased, the thickness of the sheet started to decrease. The material in the thinnest area of the side wall



FIGURE 4: Sinusoidal motion.

TABLE 1: Definitions of meshing, material model selection, and contact and boundary conditions.

Meshing	Workpiece		Mesh type: S4R Number of units: 19600							
	Tool ł	nead	Analytical rigid							
Material model selection	Workpiece Model: plastic model of shell metal Material: 1060 aluminum sheet (elastic modulus = 70 GPa; Poisson's ratio = 0.3 density = 2710 kg/m ³)									
Contact condition	Contact type between tool head and aluminum sheet: surface-to-surface									
Boundary conditions	Workpiece 6 degrees of freedom (DOFs) constrain Tool head Anticlockwise rotation around the shee									
TABLE 2: Stress and strain properties of 1060 aluminum.										
Stress (MPa)	20	44	64	77	87	91	98			
Strain	0.002	0.0169	0.0507	0.0845	0.1183	0.1352	0.169			



FIGURE 5: Finite element model of UV-SPIF.

🖶 Edit Amplitude 🛛 🕅									
Name: ultrasonic vibration									
Type: Periodic									
Time Span: Step time 🚽									
Circular freque	ency: 125600								
Starting time:	0								
Initial amplitud	le: 0								
Α	В								
1 0.03	0								
ОК	Cancel								

FIGURE 6: Simulation interface for ultrasonic vibration.

first reached the breaking limit; thus, the center part of the forming area was the most susceptible to damage. Therefore, it is necessary to control the forming depth in the z direction in order to improve the forming limit.

Figure 10 presents the displacements of the nodes in three directions along the cutaway path. U_1 , U_2 , and U_3 are the spatial displacements on the *x*-axis, *y*-axis, and *z*-axis, respectively. It is clear that the tensile displacement on the *z*axis was the largest. The displacements on the *x*-axis and on the *y*-axis were substantially symmetric along the cutaway path. The displacement in the *z* direction determines the depth of the truncated cone to be formed. Therefore, the excessive displacement in the z direction causes the breakage of sheet metals.

3.3. Plastic Strain Analysis of UV-SPIF Area. The maximum deformation of the sheet prior to fracture represents the degree of deformation during plastic processing, and it is called the plastic limit or plasticity index. In the present simulation, data points on the cutaway path were extracted to find the plastic strain law in the forming area.

Figure 11 illustrates the variation in plastic strain along the nodal path in the forming area. It is observable that strains on the side wall of the truncated cone were symmetrically distributed. Due to the presence of breakage, the plastic strain curve was approximately 40 mm higher than the symmetry position (120 mm) of the truncated cone. This occurred because the aluminum sheet was damaged near the 40 mm position in the forming area. If the lower layer of the tool head just breaks the sheet, the plastic strain at this location can be used as the ultimate plastic strain.

Figure 12 displays the plastic strain component curves, where PE_{11} , PE_{22} , and PE_{33} represent plastic strains along the *x*-axis, the *y*-axis, and the *z*-axis, respectively, and PE_{12} is the plastic strain in the *x*-*y* plane.

Figure 13 presents the distribution of PE_{11} in the *x* direction. It is discernible that plastic variables followed a parabolic distribution along the nodal path. When PE_{11} reached the maximum value of 1.25, it started to decrease. As the plastic limit was not attained, the plastic strain on the *x*-axis was not the main reason for the failure of the sheet. The distribution of PE_{22} in the *y* direction is displayed in Figure 14. It is clear that the distribution of PE_{22} was exactly opposite to that of PE_{11} . Along the nodal path, PE_{22} decreased from its maximum value of 1.154 to the minimum. However, afterward, PE_{22} again increased to its maximum value. Similarly, the plastic strain component on the *y*-axis did not reach the ultimate strain; therefore, PE_{22} was not the main reason for the facture of the sheet.

The distribution of PE_{12} in the *x*-*y* plane is illustrated in Figure 15. The sheet was layered in the *x*-*y* plane, and the feed and the rotation of the tool head in each layer formation caused the material to flow toward the direction of least resistance. Therefore, a small feed rate and a small rotational speed made the material less strained in the *x*-*y* plane; consequently, the plastic strain limit was enhanced.

The distribution of PE₃₃ in the *z* direction is displayed in Figure 16. It is noticeable that plastic strains were distributed approximately evenly along the nodal path. PE₃₃ reached its highest value of about -1.5 at the failure position. As the depth of formation increased, the material gradually reached its strain limit and, eventually, experienced a fracture. Therefore, in UV-SPIF, the damage of the aluminum sheet mostly occurred in the direction perpendicular to the *z*-axis.

3.4. Influences of Ultrasonic Vibration Parameters on Formability. It is already proven that cracking occurs in the thinnest area of the side wall of the truncated cone. Therefore, the maximum forming angle before fracture can



FIGURE 7: Simulated stress map.



FIGURE 8: Half-plane viewport and node path.



--- Thinning curve of thickness forming area

FIGURE 9: Variation in sheet thickness along the cutaway junction path.

characterize the formability of the aluminum sheet. The status variable 0/1 was set in the field output of ABAQUS. When the mesh deformed beyond the preset fracture strain value, the status variable became 0 and the mesh element was deleted. When the mesh deformation was less than the preset fracture strain value, the status variable became 1 and the cell mesh remained intact. The preset strain value at the breaking point was obtained by using an HT2402-type electronic tensile tester.

3.4.1. Influences of Ultrasonic Vibration Amplitude on the Forming Angle. In UV-SPIF, ultrasonic vibration frequency and amplitude significantly affect the forming limits of sheet metals.

In order to study the influences of different vibration amplitudes ($0 \mu m$, $2 \mu m$, $4 \mu m$, $6 \mu m$, $8 \mu m$, and $10 \mu m$) on the forming angle, the vibration frequency (*f*) was set to 24 kHz. The amplitude-forming angle curve is illustrated in Figure 17. The starting point of the curve represents a general SPIF



FIGURE 10: Displacements of nodes in three directions along the cutaway path.



FIGURE 11: Equivalent plastic strain curve along the nodal path.

process with no ultrasonic vibration, whereas the remaining points denote the forming angles at different amplitudes. Under ultrasonic vibration, the forming angle of the aluminum sheet was improved to some extent. The forming angle gradually increased with the increasing vibration amplitudes from $0 \,\mu\text{m}$ to $6 \,\mu\text{m}$ and then started to decrease. In summary, the 1060 aluminum sheet yielded the largest forming angle at a frequency of $6 \,\mu\text{m}$ and a frequency of $24 \,\text{kHz}$.

However, ultrasonic vibration caused a decrease in the yield strength of the aluminum sheet, which can be attributed to the movement of the lattice structure in the sheet. Consequently, the movements of slip systems expedited the plastic deformation of the sheet. This phenomenon is also termed as the softening effect of ultrasonic vibration. Due to a change in amplitude, slip systems of the aluminum sheet influenced each other and caused a hindrance to dislocation motion. In addition, the internal metal grain boundary area of the sheet was heavily accumulated; hence, the intensity of the external force was further increased to circumvent obstacles between dislocations, and it resulted in a hardening effect of ultrasonic vibration. Therefore, it can be inferred that both softening and hardening phenomena occurred in UV-SPIF; however, the softening phenomenon preceded the hardening effect.



FIGURE 12: Plastic strain component curves along the nodal path.



FIGURE 13: Distribution of PE₁₁.



FIGURE 14: Distribution of PE₂₂.

3.4.2. Effects of Ultrasonic Vibration Frequency on the Forming Angle. In order to study the influences of different vibration frequencies (0 kHz, 10 kHz, 15 kHz, 20 kHz, 25 kHz, 30 kHz, 35 kHz, and 40 kHz) on the forming angle, the amplitude was set to $6 \,\mu$ m. The frequency-forming angle curve is exhibited in Figure 18.

The starting point represents an ordinary SPIF process without ultrasonic vibration. At an amplitude of $6 \mu m$, the forming angle of the ultrasonically processed aluminum sheet was found to be larger than that of the ultrasonic-free one. With increasing vibration frequencies from 10 kHz to 25 kHz, the forming angle of the sheet tended to increase.

However, as the frequency continued to increase from 25 kHz to 40 kHz, the forming angle exhibited a downward trend. Therefore, it can be inferred that vibration frequency caused a nonlinear effect on the forming angle. The 1060 aluminum sheet yielded the largest forming angle at f = 25 kHz.

UV-SPIF changed the continuous rolling contact between the tool head and aluminum sheet to a high-frequency intermittent contact and enhanced the formability of the sheet. As the vibration frequency increased, the number of alternating contacts between the tool head and aluminum sheet also (per unit time) increased significantly.



FIGURE 15: Plastic components in the x-y plane.



FIGURE 16: Plastics component in the z direction.



FIGURE 17: Effects of amplitude on the forming angle.



FIGURE 18: Effects of vibration frequency on the forming angle.

This promoted the movements of slip systems and improved the formability. When the frequency was >25 kHz, the number of alternating contacts between the tool head and the sheet was too large, thus exceeding the fatigue limit of the material. Therefore, it can be posited that larger vibration frequencies cause a significant decrease in the forming angle.

4. Experiments on UV-SPIF

4.1. Experimental Setup. The UV-SPIF system mainly consisted of an ultrasonic generator, a piezoelectric ceramic transducer, and an amplitude transformer. The ultrasonic generator produced an electrical signal and transmitted it to the transducer. The transducer then converted the electrical signal into mechanical vibration, which was further amplified by the amplitude transformer. Finally, the amplified vibration was transmitted to the tool head.

The frequency (f) of the ultrasonic generator (maximum output power of 2 kW) could be adjusted. As a stepless frequency modulation ultrasonic generator was used in the present experiment, its amplitude could not be directly adjusted. The relationship between power and amplitude can be expressed by equation (4). According to the wave energy theory, the energy density of a wave is proportional to the square of the amplitude:

$$\rho_{\rm e} = \frac{\overline{P}}{S} = \frac{1}{2} K_{\rm e} A^2, \tag{4}$$

where \overline{P} is the average energy flow of waves passing through the unit area *S* per unit time. In the aforesaid expression, $K_e = \rho c \omega^2$, where ρ is the density of the medium material (7.8 × 10³ kg/m³), *A* is the amplitude, *c* is the speed of wave (5200 m/s), and ω is the angular frequency. Therefore, for the maximum output power of 2 kW, the maximum value of *A* was found to be 50 μ m (without considering any energy loss). The ultrasonic generator was adjusted to different frequencies (40 W, 80 W, 120 W, 160 W, and 200 W), and the corresponding amplitudes were measured by using a CYS-J200 digital amplitude-measuring instrument (measurement range of 0~1300 μ m) (Figure 19) (Table 3).

The vibration frequency of the amplitude transformer was set to 25 kHz (Figure 20). The tool holder and the

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FIGURE 19: Amplitude-measuring instrument.

TABLE 3: Experimental results.										
Power (W)	40	80	120	160	200					
Amplitude (µm)	2.04	4.13	6.14	8.13	10.17					



FIGURE 20: Ultrasonic vibration spindle system.

transducer were linked by a special coupling, and the tool head was connected with the amplitude transformer by a locknut. The tool holder was finally mounted on a HAAS high-speed CNC milling machine (Figure 21). The KISTLER 9257B triaxial force transducer was used to measure forming forces. Sensors and charge amplifiers were used to monitor



FIGURE 21: Forming device.

the stability of the experimental process. When the force curve was regular, the experimental process remained stable; however, when large fluctuations occurred in the force curve, the experimental process was considered unstable.

The chemical composition of the AL1060 alloy sheet is depicted in Table 4. The tool head (diameter of 10 mm) material was quenched high-speed steel. The layer spacing during the forming process was set to 1 mm, and the forming angle was 45°. The forming trajectory was generated in UG8.0 software (Unigraphics NX) (Figure 22). The machining program was inputted into the HASS high-speed CNC milling machine in order to control the motion of the tool head.

4.2. Effects of Ultrasonic Vibration Parameters on the Forming Angle. Six sets of amplitude experiments (each repeated three times) were carried out at a fixed frequency of 25 kHz, and their arithmetic mean was considered as the result. Figure 23 presents an error bar of six sets, and the relative standard deviation of each group was found to be less than 5%. Figure 24 depicts the effects of different vibration amplitudes on the forming angle. The starting point of the curve represents an ordinary SPIF process without ultrasonic vibration.

When the frequency was constant at 25 kHz, the forming angle increased first and then gradually decreased with increasing amplitude, and the maximum value was achieved at around 6 μ m. When the amplitude was 0 μ m, the smallest forming angle was obtained, which can be ascribed to the softening effect. At larger amplitudes, the material absorbed more ultrasonic energy per unit time, thus the softening phenomenon became more significant. However, when the amplitude exceeded 6 μ m, the impact of the tool head on the

TABLE 4: Chemical composition of the AL1060 aluminum alloy (%, mass fraction).



FIGURE 22: Forming track in UV-SPIF.



FIGURE 23: Error bar graph of amplitude experiments.

sheet generated considerable strains in the z direction, and the material became more susceptible to cracking. Consequently, the ultimate forming angle of the sheet decreased with increasing amplitude.

Similarly, when the amplitude was fixed at $6 \,\mu$ m, eight sets of frequency experiments (each repeated three times) were performed, and their arithmetic mean was considered as the final result. Figure 25 presents an error bar of eight sets, and the relative standard deviation of each group was found to be less than 5%. Figure 26 illustrates the effects of vibration frequency on the forming angle.

When the amplitude was constant at $6 \,\mu m$, the forming angle increased first and then started to decrease with the increasing frequencies, and the maximum value was attained



FIGURE 24: Effects of vibration amplitude on the forming angle.



FIGURE 25: Error bar graph of frequency experiments.



FIGURE 26: Effects of vibration frequency on the forming angle.

at around 25 kHz. When the frequency was 0 kHz, the smallest forming angle was achieved because UV-SPIF changed the continuous rolling contact between the tool head and the aluminum sheet to a high-frequency intermittent contact. As the intensity of frequency increased, the number of alternating contacts between the tool head and the aluminum sheet (per unit time) also increased. This promoted the movements of slip systems and improved the formability; thus, the sheet became susceptible to fracture at larger forming angles. When the frequency was >25 kHz, the number of alternating contacts between the tool head and the aluminum sheet was too large, thus exceeding the fatigue limit of the material. Therefore, larger vibration frequencies caused a significant decrease in the forming angle of the aluminum sheet.

5. Conclusion

- (1) In UV-SPIF, the center position of the side wall of the truncated cone was the thinnest area. The thinning rate was symmetrically distributed from the center of the side wall to the bottom and to the top. The center position of the truncated cone was the most susceptible to fracture. In the plastic forming area, the aluminum sheet first reached its strain limit along the *z*-axis. Due to a small feed and a small rotational speed, the increase in strain in the *x-y* plane was smaller, thus resulting in a much higher forming limit.
- (2) When the vibration frequency was constant at 25 kHz and the amplitude was changed from $0 \,\mu$ m to $6 \,\mu$ m, a softening effect occurred, and consequently, the formability of the sheet was improved. When the ultrasonic amplitude was greater than $6 \,\mu$ m, the impact of the tool head on the sheet caused larger strains in the *z* direction; thus, the formed part became more susceptible to cracking.
- (3) When the amplitude was fixed at 6μ m and the frequency was changed from 0 kHz to 25 kHz, the number of alternating contacts between the tool head and the aluminum sheet (per unit time) increased significantly. This promoted the movements of slip systems and improved the formability. When the frequency was >25 kHz, the number of alternating contacts between the tool head and the sheet was large and exceeded the fatigue limit of the material. Therefore, it can be posited that larger vibration frequencies cause a significant decrease in the forming angle.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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