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ARTICLE

Influence of Ellipse Bidirectional Ultrasonic Vibration Incremental Forming on Mechanical Properties and Microstructure of 6061 Aluminum Alloy Thin-Walled Parts

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Abstract: To improve the processing and practical performance during the manufacture of complex thin-walled parts, the mechanical properties and microstructure revolution of complex thin-walled parts of 6061 aluminum alloy prepared by ellipse bidirectional vibration incremental forming were investigated. The traditional incremental forming, vertical unidirectional ultrasonic vibration incremental forming, and ellipse bidirectional ultrasonic vibration incremental forming methods were compared. To verify the enhancement effect on forming quality and mechanical properties of complex thin-walled parts of aluminum alloy, the microhardness and residual stress of as-prepared parts were analyzed, and their morphologies were observed. The microhardness test results show that the ellipse ultrasonic incremental forming process can soften the material and improve its plasticity and toughness, thereby promoting the formability of thin-walled parts of aluminum alloy. A great number of dimples appearing on the fracture surface further confirms this conclusion. The microstructure characteristic on the surface of as-prepared parts shows that the ellipse bidirectional vibration incremental forming method can significantly improve the surface quality. In addition, the ellipse bidirectional ultrasonic vibration incremental forming method can form a residual compressive stress layer on the surface of 6061 aluminum alloy, which improves the fatigue resistance performance of complex thin-walled parts.

Key words: incremental forming; bidirectional ultrasonic vibration; aluminum alloy; mechanical properties; residual stress; microstructure

As a commonly used engineering material in 6XXX series aluminum alloys, 6061 aluminum alloy is widely applied in aircraft, ship, automobile, and furniture due to its lightweight, high strength, good elasticity, easy processing ability, and good corrosion resistance[1–2]. The thin-walled parts of 6061 aluminum alloy usually serve under multiple environments of high temperature, corrosion, and impact load[3], which easily result in stress concentration. In addition, cracks can be easily initiated and expand between the interior and surface of the thin-walled parts, which eventually lead to fracture or even damage the entire mechanical structure. Thus, higher requirements on formability and fatigue resistance of complex thin-walled parts of 6061 aluminum alloy have been proposed.

Traditional stamping method can be applied to process the sheet metal parts[4–6], but it is restricted due to the inferior flexibility and high cost. Sheet metal incremental forming technique is a new type of die-less forming technique, which introduces the layered manufacturing in rapid prototyping manufacturing technology[7]. This method has the advantages of model-free manufacturing, good processing capacity of thin-walled parts with complex curved surfaces, and low cost.

Wang et al[8] studied the effects of different temperatures on the incremental forming of 2024 aluminum alloys and found that with increasing the temperature, the forming angle limit of 2024-T6 aluminum alloy is increased. Besides, the incremental forming at high feeding rate can improve the forming limit of parts. Kumar et al[9] discussed the effects of forming tool shape, tool diameter, wall corner, step size, plate thickness, and tool rotation on the single-point forming of 2024 aluminum alloy sheet. Kilani et al[10] analyzed the

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influence of the head diameter and feeding rate of forming tool on the axial force and surface roughness of parts prepared by single-point-enhanced forming method. Esmaeilpour et al[11] simulated the single-point incremental forming process of 7075 aluminum alloy by the multi-parameters finite element method to analyze the hardening law of 7075 aluminum alloy during the forming process. Vosniakos et al[12] investigated the asymmetric sheet metal parts prepared by single-point incremental forming and discussed the effect of tool-path on incremental forming through simulation. It is worth noting that the equivalent plastic strain distributed on the plate during single-point incremental forming is uneven, and the rupture phenomenon can hardly be controlled. Therefore, the multi-point composite incremental forming is proposed, which improves the successive deformation performance and efficiency. Gao et al[13] conducted the fracture limit simulations and manufacture experiments on hyperbolic truncated cones through a double-sided multi-point incremental forming equipment to find the fracture criteria. Most research focuses on the optimization of processing parameters to ameliorate the forming quality and forming limits of incremental forming process. However, the insufficient formability seriously restricts the application of incremental forming technique for high-strength metals and complex panels[14]. It is revealed that the multi-energy effect of mechanical field, thermal field, electric field, magnetic field, and ultrasonic field can greatly influence the forming mechanism, mechanical behavior, and microstructure evolution of metal materials[15–18]. The energy-assisted manufacture techniques, including ultrasonic incremental forming process, can significantly ameliorate the formability and usability of metal parts, therefore gradually becoming a new development direction for manufacture.

With the wide application of ultrasonic assistance technique, the ultrasonic incremental forming has been extensively researched. Khan et al[19] verified that the incremental waves can reduce the forging force and friction between the lower surface of workpiece and the upper surface of mold, thus improving the forming effect. Yao et al[20] developed an ultrasonic vibration plastic processing method and a single-point incremental forming device, and conducted finite element simulations and forming tests with 1060 aluminum alloy sheet. The softening effect is dominant under the low-frequency vibration condition, whereas the hardening effect is dominant under the high-frequency vibration condition. Yang et al[21] studied the influence of ultrasonic vibration single-point incremental forming on the formability of metal plates, and found that ultrasonic vibration can effectively improve the forming limit of the alloy plate. Li et al[22] revealed the influence of ultrasonic vibration on deformation behavior by simulation based on ANSYS/LS-DYNA software. It is proved that the modified constitutive model considering the softening effect can improve the prediction accuracy. Zhang et al[23] conducted simulations and tests of ultrasonic-assisted incremental forming to prepare metal sheet parts. The simulation can accurately predict the influence of tool size and other parameters on forming force and rebound rate. Liu et al[24] combined ultrasonic vibration with two-stage aging molding and found that the rebound rate of aluminum alloy specimens decreases in the ultrasonic incremental forming process. These researches mainly focus on the deformation mechanism and process parameters of ultrasonic incremental forming. The multi-coupling actions of ultrasonic effect, work hardening, heat softening, and stress superposition induced by ultrasonic have been investigated[25–28]. It is clear that the softening effect can decrease the forming force and improve the friction condition between the tool and the sheet, which is beneficial to the improvement in forming limit and manufacture ability of alloys[29–33]. However, these researches only consider the one-way ultrasonic incremental forming process. Multi-dimensional ultrasonic vibration device is rarely used for incremental forming. Thus, the influence of the enhanced ultrasonic effect on mechanical behavior, forming mechanism, and surface quality of aluminum alloy is still obscure.

Therefore, this research proposed a bidirectional ultrasonic vibration incremental forming technique. The microhardness, surface morphology, fracture morphology, and residual stress were analyzed to investigate the mechanical properties and microstructure revolution of the thin-walled plates of 6061 aluminum alloy after the traditional single-point incremental forming (SPIF), vertical one-way ultrasonic vibration incremental forming, and bidirectional ultrasonic vibration incremental forming. This research provides design guidance for the complex thin-walled plates of high-strength alloys.

1 Principle

The ultrasonic vibration plastic forming of metal materials is related to the application of controllable ultrasonic vibration with specific direction, frequency, and amplitude on the processing equipment (tool, die) in the classic plastic processing system. Thus, the ultrasonic energy assists the plastic forming process of metal materials. The ultrasonic vibration device is generally composed of ultrasonic generator, transducer, vibration bar, tool head, and workpiece, as shown in Fig.1.

According to different vibration modes, the ultrasonic incremental forming of metal materials has two types: the vertical unidirectional ultrasonic vibration incremental forming (VUUVIF) and the ellipse bidirectional ultrasonic

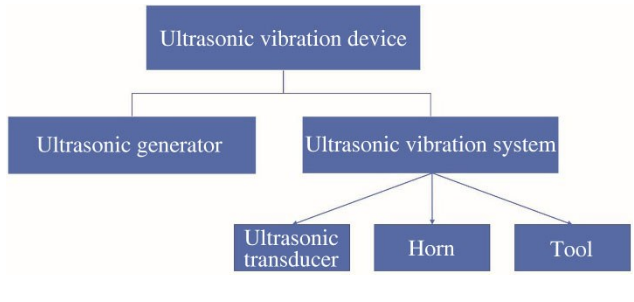

Fig.1 Schematic diagram of ultrasonic vibration device

vibration incremental forming (EBUVIF). Currently, the researches on ultrasonic incremental forming mainly focus on VUUVIF, which can reduce the forming force and improve the forming performance. As shown in Fig. 2a, the hardened pit and residual compressive stress area generated by the impact of forming tool on the workpiece surface are located in the current processing layer. On the one hand, the impact-strengthened layer on the surface of machined workpiece will be destroyed during the plastic flow of material. On the other hand, the generated impact-strengthened layer may increase the deformation resistance of material and the rupture risk. According to Fig. 2b, EBUVIF can obviously increase the contact area between the forming tool and the workpiece. The bidirectional ultrasonic vibration system enhances the assisting energy to soften the metal materials. Besides, the ellipse bidirectional vibration trajectory can achieve synergistic processing of surface strengthening treatment and high-performance plastic treatment by the impact of the machined area on the plate. The interaction effect between the surface strengthening and plastic flow deformation of material is avoided. Therefore, EBUVIF method can better improve the forming ability and mechanical properties of metal materials.

2 Experiment

A bidirectional composite ultrasonic vibration system was designed and manufactured to conduct the ultrasonic vibration incremental forming process, which consisted of *X*-axis and *Z*-axis ultrasonic vibration devices fixed on the vibration system foundation. Each ultrasonic vibration device included an ultrasonic generator, a transducer, a frequency filter, a phase shifter, a vibration bar, and other components. The perpendicular pair of vibration bars were connected to the vibration platform, where the process mould and fixture were installed. Fig. 3 shows the ultrasonic vibration system and the

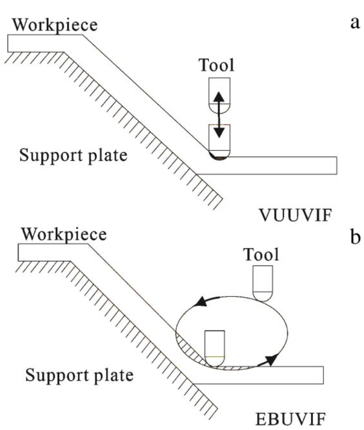

Fig.2 Schematic diagrams of VUUVIF process (a) and EBUVIF process (b)

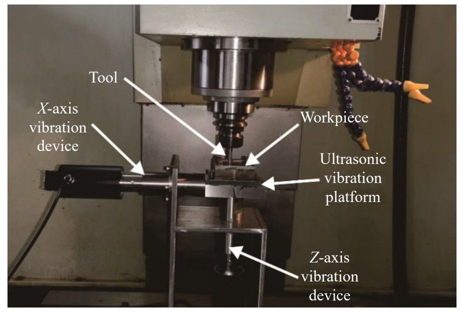

Fig.3 Appearance of ellipse bidirectional ultrasonic vibration system

forming machine. Both the ultrasonic vibration bars vibrated along a straight line at the same frequency with a certain amplitude. The vibration devices with ultrasonic waves of the same phases vibrated the vibration platform along the normal direction. The incline angle depended on the ratio of the amplitudes of the two ultrasonic vibration devices. Whereas the phases of the two ultrasonic waves differed by a quarter of one cycle. Therefore, the vibration platform vibrated according to the elliptical trajectory. The long and short axes of the ellipse were equal to the amplitude of the *X*-axis and *Z*-axis vibration devices, respectively. When only the *Z*-axis vibration device worked, the vibration platform vibrated along the vertical direction. Thus, this designed ultrasonic vibration system could realize SPIF, VUUVIF, and EBUVIF processes by adjusting the working conditions of vibration devices.

The chemical composition and mechanical properties of 6061 aluminum alloy are shown in Table 1 and Table 2, respectively. The 6061 aluminum alloy rolling sheet was cut into specimens of 80 mm×80 mm×2 mm by wire cutting machine. In the incremental forming process, the auxiliary die (Fig. 4) mainly offered the supporting effect for the machined parts, which could improve the forming qualities and shape accuracy of the parts. Then, the die was put into the square hole of the fixture, as shown in Fig. 4. The specimen of 80 mm×80 mm×2 mm was fixed above the fixture by four inner hexagon screws. Then, the specimen and the auxiliary tool were installed on the upper face of the ultrasonic vibration platform. The bidirectional composite ultrasonic vibration system was installed on the J1VMC40MB four-axis machining center, and the special ultrasonic vibration incremental forming machine was established. The traditional SPIF, VUUVIF, and EBUVIF processes were conducted to prepare the classic circular cone parts of 6061 aluminum alloy. The horizontal feeding rate of the forming tool was 500 mm/min. The rotational speed rate of the forming tool was 1000 r/min, and the longitudinal feeding value was 0.1 mm. Since a large amount of heat induced by ultrasonic effect and frictional effect was released during the process, the workpiece temperature increased rapidly, and the processing accuracy

Table 1 Chemical composition of 6061 aluminum alloy (wt%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.40–0.80	≤0.70	0.15–0.40	0.15	0.8–1.2	0.04–0.35	0.25	0.15	Bal.

Table 2 Plate thickness and mechanical properties of 6061 aluminum alloy

Thickness/ mm	Tensile strength/MPa	Yield strength/MPa	Elongation/ %
1	⩾180	⩾110	⩾14

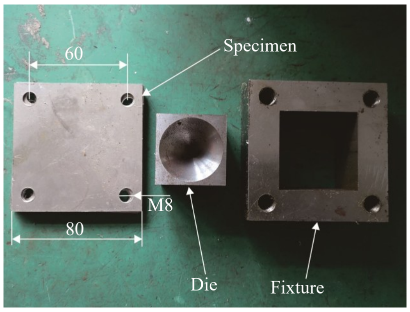

Fig.4 Appearance of specimen and auxiliary tool

was greatly affected. Therefore, the cooling system of the machining center was used to maintain the working temperature.

To investigate the effect of bidirectional ultrasonic vibration incremental forming on the mechanical properties and microstructure evolution of thin-walled parts of 6061 aluminum alloy, the microhardness, surface morphologies, and residual stress of conical parts of 6061 aluminum alloy after SPIF, VUUVIF, and EBUVIF processes were analyzed.

The microhardness tests were conducted by HMAS automatic microhardness testing system. The loading force was 2.94 N and the pressing time was 20 s. The Vickers microhardness (HV) was measured. Five indentations were applied on the specimen surface, and the average value of five measurements was used for analysis. Scanning electron microscope (SEM, TESCAN MIRA LMS, Czech Republic) with backscattered electron (BSE) mode was used to observe the surface morphology and fracture morphology of the specimens.

The nondestructive residual stress measurement is related to the measurement of acoustic, optical, magnetic, or electrical characteristics of materials, and then indirectly reflects the microhardness. To obtain the residual stress distribution on the surface of 6061 aluminum alloy specimens after SPIF, VUUVIF, and EBUVIF, the residual stress tests were conducted by X-ray diffractometer (XRD, RIGAKU company, Japan). The tube current was 1.5 mA, the tube voltage was 30 kV, the X-ray incidence angle was 35°, the alpha angle offset was 0°, K-alpha X-ray wavelength was 0.2291 pm (Cr), K-beta X-ray wavelength was 0.2085 pm (Cr), diffraction crystal plane was (2, 2, 2) with face-centered cubic structure, Young's modulus was 72.470 GPa, and Poisson's ratio was 0.341.

3 Results and Discussion

3.1 Microhardness

After SPIF, VUUVIF, and EBUVIF processes, the original sheet and the machined conical plates were cut into specimens for the microhardness tests, and the results are shown in Fig.5. It can be seen that the microhardness of 6061 aluminum alloy after VUUVIF process is significantly higher than that of raw material and the specimens after SPIF and EBUVIF processes. Compared with the that of the raw material, the microhardness of specimen after SPIF, VUUVIF, and EBUVIF processes increases by 3.74%, 17.66%, and 1.74%, respectively. This result is mainly affected by the work-hardening effect and heat effect caused by friction. Mechanical force and ultrasonic energy simultaneously exert influence on the specimens during the ultrasonic vibration incremental forming processes. The work-hardening, frictional heat softening, ultrasonic softening, ultrasonic hardening, and stress superposition effects jointly affect the mechanical properties and microstructure of metal materials. It is revealed that the softening effect is in dominant position during EBUVIF process, whereas the hardening effect is in dominant position during VUUVIF process. Therefore, it is deduced that the vertical unidirectional vibration can better improve the surface impact strengthening of thin-walled plates of 6061 aluminum alloy than the ellipse bidirectional vibration mode does. The dominant softening effect can promote the plastic flow deformation of 6061 aluminum alloy during EBUVIF process.

3.2 Morphology

The surface morphologies of the 6061 aluminum alloy raw material and 6061 aluminum alloys after SPIF, VUUVIF, and EBUVIF processes were observed by SEM, as shown in Fig.6a–6d, respectively. A large number of distinct and severe scratches caused by rolling and cutting process are uniformly distributed on the surface of the 6061 aluminum alloy raw material, as shown in Fig. 6a. Similar scratches can also be observed on the surface of the 6061 aluminum alloy after SPIF process, as shown in Fig. 6b. The inferior surface roughness of specimen after SPIF process is related to the violent friction between rolling forming tool and specimen as well as the strong extrusion force by the downward feeding tool. The 6061 aluminum alloy deforms and even tears under the huge external force action. Therefore, the scratches, cracks, and abundant metal debris appear on the surface of

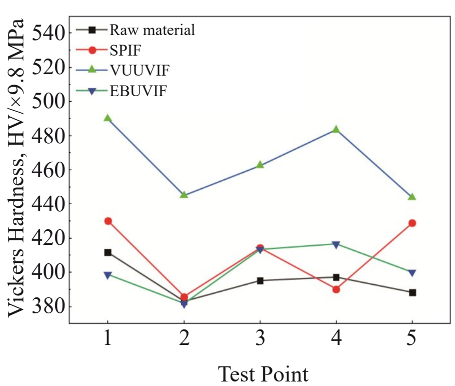

Fig.5 Microhardness results of 6061 aluminum alloy raw material and 6061 aluminum alloys after SPIF, VUUVIF, and EBUVIF processes

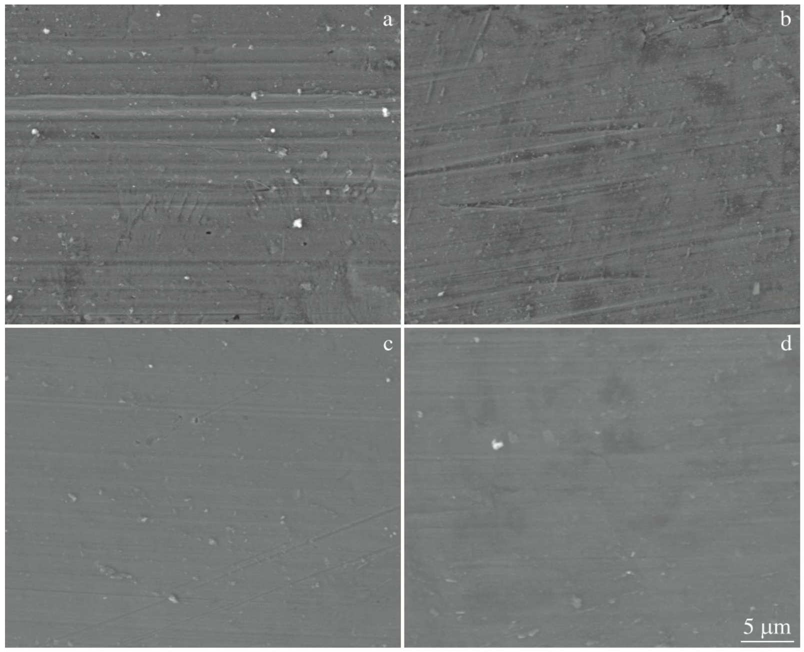

Fig.6 SEM surface morphologies of 6061 aluminum alloy raw material (a) and 6061 aluminum alloys after SPIF (b), VUUVIF (c), and EBUVIF (d) processes

6061 aluminum alloy after SPIF process. The 6061 aluminum alloys after VUUVIF and EBUVIF processes present excellent surface performance, compared with the abovementioned specimens. This is because the ultrasonic vibration can significantly improve the surface quality of metal parts, according to the ultrasonic plastic forming mechanism. On the one hand, the stress superposition and metal softening effect decrease the forming force. On the other hand, the ultrasonic vibration reduces the exposure time and contact area between the forming tool and the part, compared with those of the specimen after SPIE process. Hence, the friction condition is effectively improved. Only a few slight scratches can be observed on surface of specimen after VUUVIF process. It is inferred that these uniform scratches may be caused by the abundant shedding debris, which are extruded by the feeding tool and high-speed rolling tool. EBUVIF process further improves the surface quality of 6061 aluminum alloy. Almost no evident scratches or cracks appear on the specimen surface. Even the scratches caused by rolling and wire-cutting are ameliorated to a certain extent.

The fractures morphologies of 6061 aluminum alloys after SPIF, VUUVIF, and EBUVIF processes are shown in Fig. 7. According to Fig. 7a, the fracture surface of specimen after SPIF process is uneven, and many perfect circular dimples of different sizes (10 – 50 μm) are distributed on the fracture surface. This phenomenon implies that some dimples prefer to nucleate at the secondary phases due to the weak adhesion between strengthening phases and metal substrate or the fracture of strengthening phases. The dimples preferentially grow up and merge with the adjacent tiny dimples, finally resulting in the big dimples in Fig. 7a. Before fracture, large plastic deformation occurs around the dimples. This is consistent with the excellent toughness of 6061 aluminum alloy at room temperature.

Fig. 7d shows the fracture surface of specimen after VUUVIF process. It can be seen that the fracture surface has a sharp corner, which is caused by the stress concentration generated by the discontinuous plastic deformation. The fracture surface of the specimen after VUUVIF process is flatter than that after SPIF process. Besides, only some extremely tiny and shallow dimples are distributed on the fracture surface. Big dimples can barely be observed. This is because the hardening effects induced by ultrasonic vibration and mechanical force can enhance the mechanic properties of 6061 aluminum alloy and restrict the nucleation and growth of dimples. This result is consistent with the microhardness test results. Due to the large shear load generated by the vertical unidirectional ultrasonic vibration, some shear dimples nucleate at the secondary phase particles and grow up until the sheet rupture. Then, some particles fall off, while others remain and exist in the dimple, as shown in Fig. 7f. When the plastic deformation reaches the deformation limit of 6061 aluminum alloy, the generation and growth of dimples stop, a large number of tearing edges appear, and the dimples are connected by the tearing edges. Two adjacent tearing edges gradually expand into a cleavage plane, and those tiny dimples are distributed near the tearing edges or on the cleavage plane. These phenomena all indicate the mixed fracture mode of ductile and quasi-cleavage fracture. Generally, this method significantly enhances the mechanical properties of aluminum alloy sheet with 1 mm in thickness, but the plastic deformation is inferior.

EBUVIF process impacts the specimen surface at a certain inclined angle. In addition, its unique design of double-

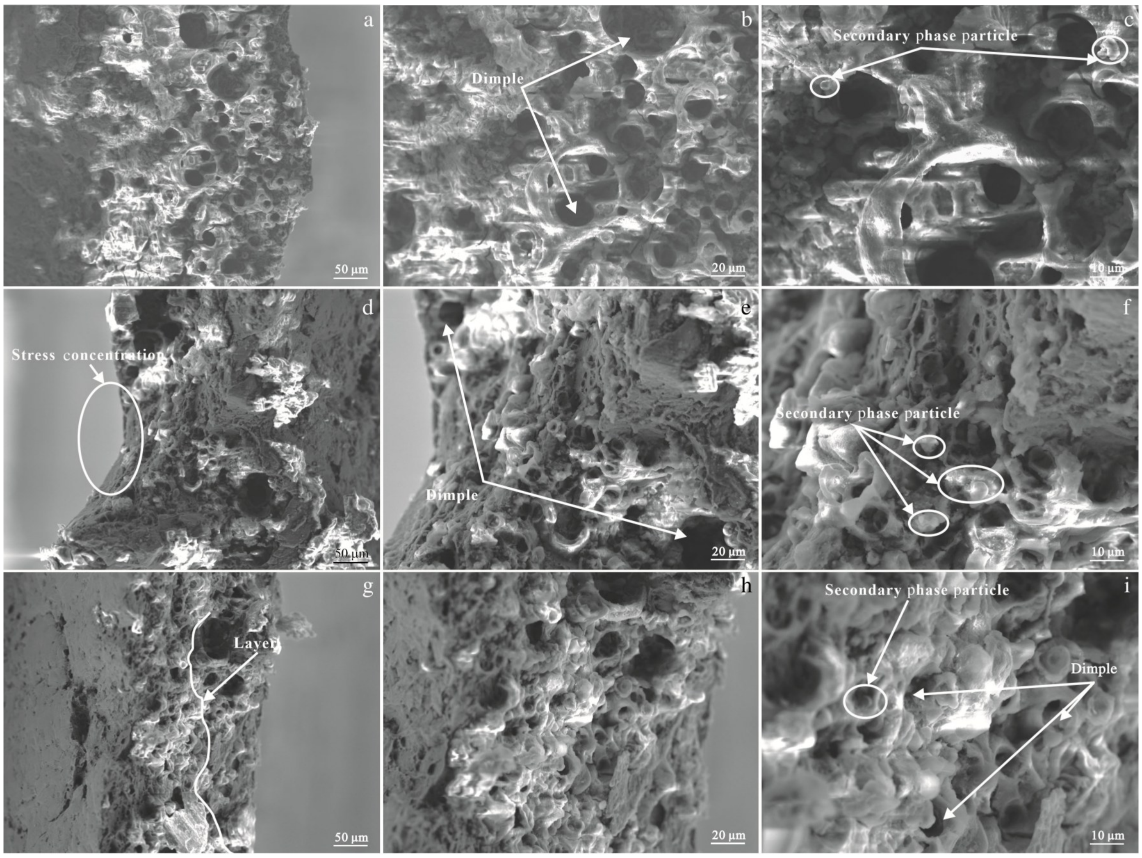

Fig.7 SEM fracture morphologies of 6061 aluminum alloys after SPIF process (a–c), VUUVIF process (d–f), and EBUVIF process (g–i)

vibration enhances the ultrasonic effect, which significantly softens the metal materials and improves the plasticity. Fig.7g shows the fracture morphology of the 6061 aluminum alloy after EBUVIF process. A few big dimples and a large number of tiny dimples are distributed on the fracture surface. This is because the work hardening, heat softening, ultrasonic softening, stress superposition, and ultrasonic hardening effects simultaneously exert influence on the aluminum alloy sheet during EBUVIF process. On the one hand, the softening effect promotes the generation of dimples. On the other hand, the hardening action suppresses the growth of dimples. Moreover, the softening effect is dominant. With continuously increasing the plastic deformation during EBUVIF process, nucleation and growth of dimples can be observed near the secondary phase particles. Before the metal material reaches its plastic deformation limit, the substrate material around the dimples undergoes large plastic deformation. Therefore, EBUVIF process leads to the ductile fracture.

3.3 Residual stress

To investigate the residual stress distribution of 6061 aluminum alloys after SPIF, VUUVIF, and EBUVIF processes, the residual stress tests were conducted by XRD residual stress testing system. According to the principle of equal angle in the circumferential direction and equal distance in the depth direction, five representative testing points were selected on the inner wall of the conical parts, as shown in Fig.8.

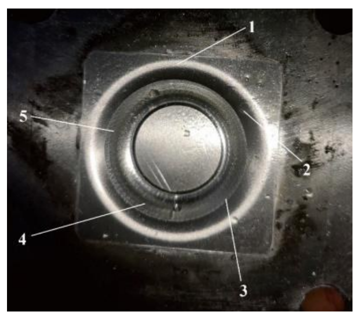

Fig.8 Appearance of specimen and test point positions for residual stress tests

The residual stress test results of 6061 aluminum alloys after SPIF, VUUVIF, and EBUVIF processes are shown in Fig. 9 – Fig. 11, respectively. According to Fig. 9a – 9d, the residual stress at point 1–point 4 is mainly compressive stress, whereas that at point 5 is tensile stress, as shown in Fig.9e. It is deduced that the missing support from the mould results in the metal material unit in the bottom of the conical part with tensile stress state of double-axis. Fig. 10 shows the residual stress results of 6061 aluminum alloys after VUUVIF process. The compressive stress is generated at all five testing points. The maximum residual compressive stress appears in the bottom of the conical part, because the forming tool of vertical vibration can impact the bottom of the conical part at right position in the upright angle with maximum ultrasonic energy,

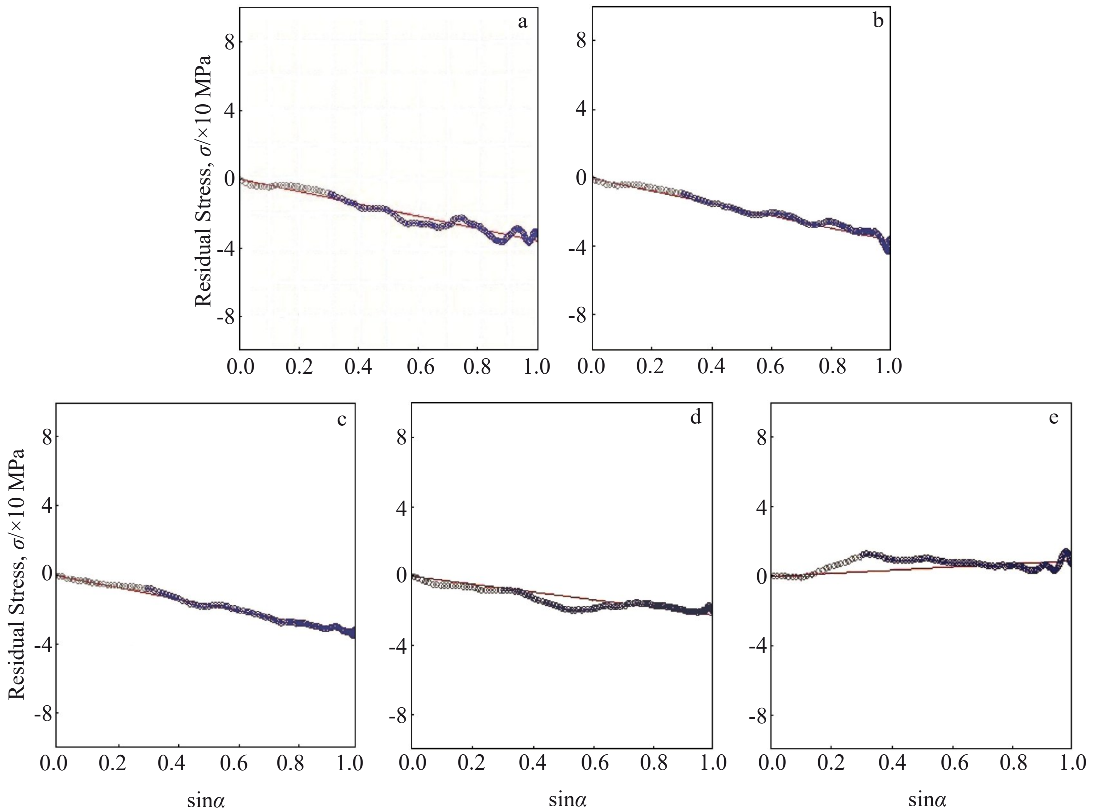

Fig.9 Residual stress curves of point 1 (a), point 2 (b), point 3 (c), point 4 (d), and point 5 (e) of 6061 aluminum alloys after SPIF process

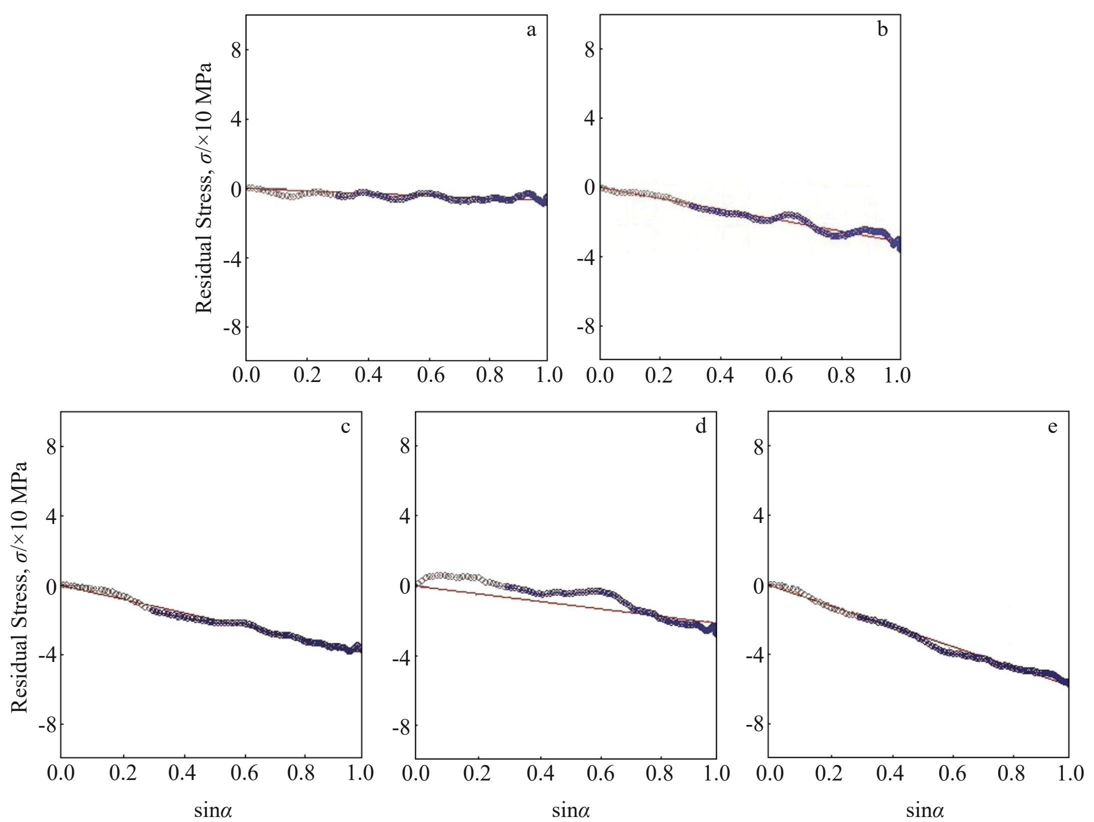

Fig.10 Residual stress curves of point 1 (a), point 2 (b), point 3 (c), point 4 (d), and point 5 (e) of 6061 aluminum alloys after VUUVIF process

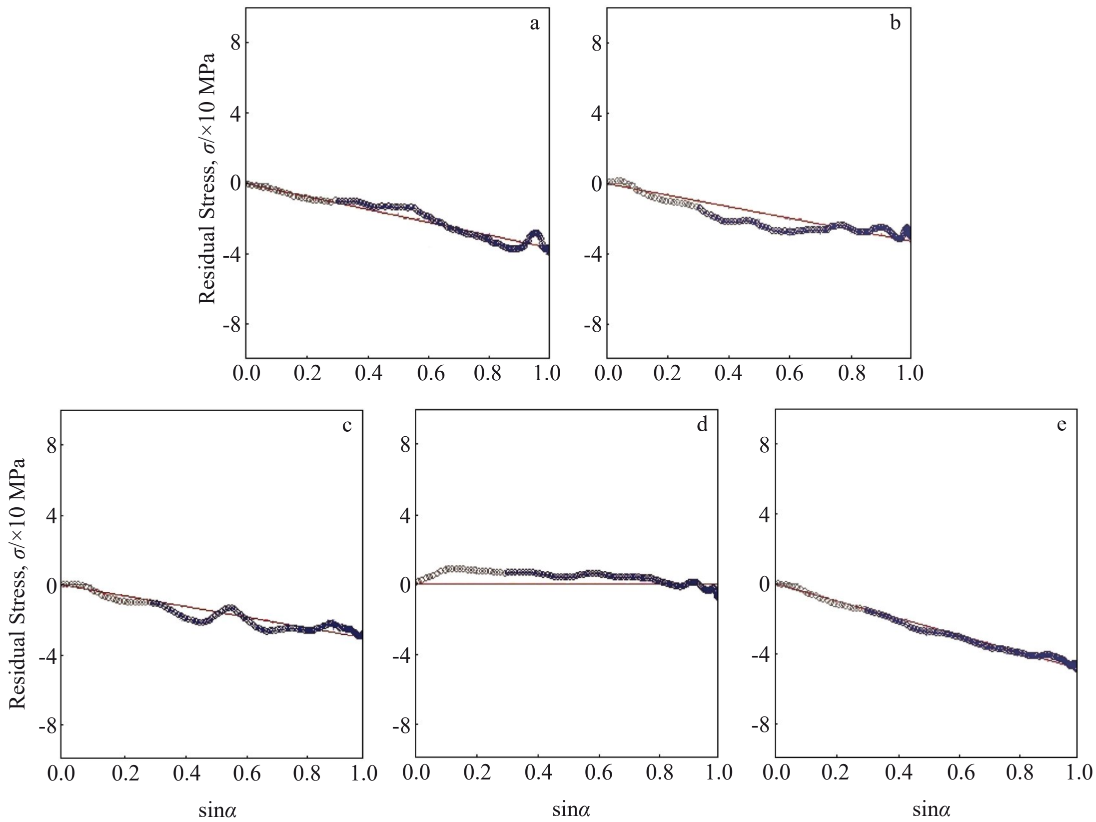

Fig.11 Residual stress curves of point 1 (a), point 2 (b), point 3 (c), point 4 (d), and point 5 (e) of 6061 aluminum alloys after EBUVIF process

thereby resulting in the maximum hardening effect and maximum residual compressive stress. But the forming tool of vertical vibration can hardly exert impact effect on the top area of the conical part. The minimum residual compressive stress appears at point 1. According to Fig.11, the distribution of residual stress on the conical part after EBUVIF process is relatively uniform at most test points, except the point 4. It is inferred that the ellipse bidirectional vibration mode can promote the forming tool to impact different locations on the conical part in appropriate angle, including the sidewall and the bottom on the conical part. Large ultrasonic energy and special vibration design lead to the compressive deformation of conical part. However, the tensile stress curve in Fig. 11d indicates that there is no compressive deformation or residual stress at point 4. This is because the forming tool with mismatched head cannot reach the junction between the sidewall and the bottom, therefore producing impact action.

As a result, the residual compressive stress layer is generated on the surface of 6061 aluminum alloy parts after SPIF, VUUVIF, and EBUVIF processes. The residual compressive stress is beneficial to improve the fatigue resistance of metal parts. But these manufacture methods produce different distributions of residual compressive stress on the conical parts. Therefore, the optimization of machining dwell time, the forming tool size, and the vibration mode should be further investigated to improve the distribution of residual compressive stress on the machined product and to ameliorate the fatigue resistance.

4 Conclusions

1) The vertical unidirectional ultrasonic vibration incremental forming (VUUVIF) process can achieve the maximum microhardness of conical part of 6061 aluminum alloy. The microhardness of the conical parts after the single-point incremental forming (SPIF) and ellipse bidirectional ultrasonic vibration incremental forming (EBUVIF) is similar to that of the raw material of 6061 aluminum alloy. Moreover, the scratches on surface of the conical part after EBUVIF process are even ameliorated, compared with those of raw materials. The hardening effects including the work-hardening and ultrasonic strengthening are in the dominant position during VUUVIF process. EBUVIF method intensifies the heat softening, ultrasonic softening, and stress superposition effects, which hinders the influence of hardening effects. It is deduced that low strength and weak rigidity of 6061 aluminum alloy sheet are related to this phenomenon. In addition, EBUVIF process can improve the plastic flow deformation of 6061 aluminum alloy for better manufacture of complex thin-walled plates.

2) The surface quality of the conical part after SPIF process barely changes, compared with that of raw material. The ultrasonic vibration can dramatically improve the surface quality of plastically deformed part. Only a few slight scratches can be observed on the part surface after VUUVIF process. EBUVIF process can further improve the surface quality of the conical part. Barely no defects appear on the

conical part after EBUVIF process.

3) The conical part after SPIF process has a lot of dimples with different sizes, indicating the great plastic deformation of 6061 aluminum alloy at room temperature. A few big dimples appear on the fracture surface of the conical part after VUUVIF process, which further verifies that the vertical unidirectional ultrasonic vibration can enhance the hardening effects of metal materials and hinder the plastic deformation. EBUVIF process exerts the work hardening, heat softening, ultrasonic softening, stress superposition, and ultrasonic hardening effects on 6061 aluminum alloy, and the softening effect is in the dominant position. Except a few big dimples, a great number of tiny dimples appear on the fracture surface of 6061 aluminum alloy after EBUVIF process.

4) The residual compressive stress is beneficial to improve the fatigue resistance of metal parts. Vertical bidirectional ultrasonic vibration impacts the bottom of the conical part in an upright angle. Therefore, the maximum microhardness and maximum compressive residual stress are obtained at the part bottom. The forming tool with vertical vibration mode impacts the side wall of the conical part in an inclined angle, which decreases the impact energy and the hardening effects on the side wall. The ellipse vibrated forming tool impacts the side wall and the bottom of the conical part in an appropriate angle. The distributions of residual compressive stress between the side wall and the bottom are different.

5) The optimization of machining dwell time, forming tool size, and vibration mode should be further investigated to improve the distribution of residual compressive stress of the manufactured parts. EBUVIF process has great advantages to improve the plastic deformation capacity and fatigue resistance performance, presenting great potential in the manufacture of complex thin-walled parts of aluminum alloys.

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椭圆双向超声振动渐进成形对6061铝合金薄壁件力学性能和微观结构的影响

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摘　要：为了在加工复杂薄壁件的过程中改善其工艺性能和使用性能，对6061铝合金复杂薄壁件双向振动超声渐进成形后的力学性能和微观结构进行了研究，对比了传统渐进成形、垂直单向超声振动渐进成形和椭圆双向超声振动渐进成形工艺，对成形后的试验件进行硬度测试、残余应力分析以及扫描电子显微镜观察，以验证双向渐进成形工艺对铝合金复杂薄壁件成形性能和使用性能的提升效果。硬度试验结果表明，椭圆超声振动渐进成形能够软化材料，增加材料塑性和韧性，从而提高6061铝合金成形复杂薄壁件的能力，试验件断裂面端口产生大量韧窝的现象也进一步证明了这一观点。试验件成形表面的微观形貌特征表明椭圆超声振动渐进成形在改善试验件表面质量方面具有显著优势。此外，发现椭圆超声振动渐进成形方法能够在6061铝合金表面形成残余压应力层，有利于提高薄壁件的抗疲劳性能。

关键词：渐进成形；双向超声振动；铝合金；力学性能；残余应力；微观形貌

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