

Effect of Cutting Parameters on Machining Performance and Surface Damage Behavior of Ultrasonic Rolling-Strengthened 7075 Aluminum Alloy

xiujie yue

yuexiujiea@163.com

Qilu Institute of Technology

ping zhang

Qilu Institute of Technology

hao zhang

Qilu Institute of Technology

weiquan sun

Qilu Institute of Technology

xiaomei ni

Qilu University of Technology

youqiang wang

Qingdao University of Technology

Article

Keywords: 7075-T6 aluminum alloy, Ultrasonic rolling strengthening, Cutting speed, Cutting force, Residual stress, Surface roughness, Surface damage behavior

Posted Date: August 3rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10196136/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Effect of Cutting Parameters on Machining Performance and Surface Damage Behavior of Ultrasonic Rolling-Strengthened 7075 Aluminum Alloy

Abstract: To clarify the effects of cutting parameters on the machining performance and surface damage behavior of ultrasonic rolling-strengthened 7075-T6 aluminum alloy, cutting experiments were conducted under different ultrasonic frequencies and cutting speeds. By combining a three-component dynamometer, confocal microscopy, and finite element simulation, the cutting force response, residual stress distribution, surface roughness, and surface morphology evolution of 7075-T6 aluminum alloy during cutting were systematically investigated. The results show that, as the cutting speed increased from 800 to 1200 mm/s, the three-directional cutting forces generally increased under ultrasonic frequencies of 0, 20, and 40 kHz. At the same cutting speed, the cutting forces followed the order of 0 kHz > 20 kHz > 40 kHz. Residual stress analysis indicates that obvious compressive residual stress was formed in the surface layer of all specimens. The compressive residual stress first increased and then decreased with increasing depth, and finally tended to stabilize. The maximum compressive residual stress was mainly distributed within approximately 5–13 μm below the surface. With increasing cutting speed, the maximum compressive residual stress generally decreased, whereas the specimens treated at ultrasonic frequencies of 20 and 40 kHz exhibited higher compressive residual stress levels than those treated at 0 kHz. Surface quality analysis shows that the machined surface roughness generally decreased with increasing ultrasonic frequency, with the lowest roughness obtained at 40 kHz. When the cutting speed was 1200 mm/s, the surface roughness decreased to 0.411 μm . Moreover, under the coupled effect of high-frequency ultrasonic rolling and higher cutting speed, surface defects such as grooves, material accumulation, and local tearing were significantly reduced, and the machined surface texture became finer and more uniform.

Keywords: 7075-T6 aluminum alloy; Ultrasonic rolling strengthening; Cutting speed; Cutting force; Residual stress; Surface roughness; Surface damage behavior

1 Introduction

7075-T6 aluminum alloy has been widely used in aerospace, rail transportation, and high-end equipment manufacturing owing to its high specific strength, favorable mechanical properties, and excellent engineering applicability^[1-3]. However, during machining, this alloy is prone to cutting force fluctuations, surface scratches, grooves, burr formation, and localized tearing due to its high strength, high resistance to plastic deformation, and pronounced tool-chip adhesion, which consequently deteriorate machining quality and service reliability^[4-6]. As a mechanical surface strengthening technology, ultrasonic rolling strengthening can introduce work hardening,

compressive residual stress, and gradient microstructures into the surface layer through the coupling effect of rolling action and high-frequency vibration, thereby improving the damage resistance of the surface layer^[7-9]. Nevertheless, the presence of the strengthened layer may also alter the material removal behavior and surface damage characteristics during subsequent machining^[10]. Therefore, it is of great significance to investigate the effects of cutting parameters on the machining performance and surface damage behavior of ultrasonic rolling-strengthened 7075-T6 aluminum alloy.

Extensive studies have been conducted on the machining performance and surface quality control of aluminum alloys. Zhang et al. ^[11] investigated the effects of T6I4 and T6I6 interrupted aging treatments on the machinability of 7075 aluminum alloy. The results showed that, compared with the T6 peak-aged condition, both T6I4 and T6I6 treatments significantly improved the machinability of 7075 aluminum alloy. Under the same cutting parameters, the 7075-T6I4 and 7075-T6I6 alloys exhibited lower cutting forces, cutting temperatures, and surface roughness, among which the 7075-T6I4 alloy showed the best overall performance. The combined effect of increasing cutting speed and decreasing feed rate effectively improved the surface finish of the workpiece. Jiang et al. ^[12] addressed the difficulty in regulating the mechanical properties of the machined surface during dry cutting of aerospace 7075 aluminum alloy. Based on the Oxley-Welsh theory, they established relational models involving shear flow stress and hydrostatic pressure, thereby correcting the deviations caused by the idealized assumptions of stress-strain behavior in the shear zone adopted in previous cutting models. Their study revealed that the slope K is a key indicator reflecting the combined effects of size effect and strain hardening in the shear zone of the workpiece material. The optimal dry cutting parameters were determined as $v_c=240$ m/min, $f=0.05$ mm/r, and $a_p=0.15$ mm. Under these conditions, the workpiece achieved the highest surface hardness of 174.1 HV, the best surface quality with a roughness of 0.78 μm , and the strongest load-bearing capacity.

Meanwhile, mechanical surface strengthening technologies, such as ultrasonic surface rolling and ultrasonic rolling strengthening, have attracted extensive attention because they can introduce plastic deformation, compressive residual stress, and work-hardened layers into the surface of metallic materials. Zheng et al. ^[13] prepared 7075 aluminum alloy using ultrasonic rolling strengthening and analyzed the elastic-plastic deformation induced by the loading-unloading

process during ultrasonic rolling based on Hertz theory and elastic-plastic deformation theory. By considering the effects of initial surface residual stress and plastic indentation depth, they established a residual stress model for ultrasonic rolling strengthening and concluded that the surface compressive residual stress increased with increasing static load. Pang et al. ^[14] reported that ultrasonic rolling refined the surface grains of Ti6Al4V alloy and introduced compressive stress. The spindle speed strongly affected the degree of plastic deformation, thereby altering the surface roughness, microstructure, and residual stress distribution. Compared with other spindle speeds, 200 rpm produced the lowest surface roughness of 0.049 μm , a deeper compressive stress field of 680 μm , and the greatest improvement in the fatigue resistance of Ti6Al4V alloy. Existing studies have provided an important foundation for cutting parameter optimization of aluminum alloys and mechanism analysis of ultrasonic rolling strengthening. However, the mechanical response, residual stress evolution, and surface damage behavior during the subsequent cutting process of ultrasonic rolling-strengthened 7075-T6 aluminum alloy have not yet been systematically investigated.

Based on this, ultrasonic rolling-strengthened 7075-T6 aluminum alloy was selected as the research object in this study. A single-factor experimental method was adopted, with three ultrasonic frequencies of 0, 20, and 40 kHz and three cutting speeds of 800, 1000, and 1200 mm/s. The machining performance and surface damage behavior of the material under different parameter conditions were systematically investigated. Through three-directional cutting force measurement, residual stress analysis, surface roughness measurement, three-dimensional surface morphology characterization, and finite element simulation, the effects of ultrasonic frequency and cutting speed on cutting force, compressive residual stress distribution, machined surface quality, and surface damage characteristics were analyzed. Furthermore, the material removal behavior and damage formation mechanism under the coupled thermo-mechanical effect of the ultrasonic rolling-strengthened layer and subsequent cutting process were revealed. The results can provide a theoretical basis and process reference for cutting parameter optimization, surface quality control, and stable retention of the strengthened layer in ultrasonic rolling-strengthened 7075-T6 aluminum alloy components.

2. Experimental Materials, Equipment, and Methods

2.1 Experimental Material

Commercial 7075 aluminum alloy plate was selected as the experimental material in this study, and its heat-treatment condition was T6. The heat treatment process was as follows: the 7075 aluminum alloy was placed in an SX2-2.5-10 box-type resistance furnace and heated with the furnace to 475°C. After holding for 2 h, the alloy was water-cooled to room temperature. Subsequently, it was reheated with the furnace to 140 °C, held for 12 h, and then air-cooled to room temperature. The main chemical compositions of the heat-treated 7075-T6 aluminum alloy, measured using energy-dispersive spectroscopy, are listed in Table 1. The 7075-T6 aluminum alloy was then subjected to ultrasonic rolling strengthening treatment. The initial specimen size was 260×260 mm, and after ultrasonic rolling strengthening, the specimens were cut into 10×10×10 mm blocks using wire electrical discharge machining.

Table 1 Chemical composition of 7075-T6 aluminum alloy

Element	Zn	Mg	Cu	Cr	Fe	Si	Mn	Ti	Al
Percentage/%	5.1-6.1	2.1-2.9	1.2-2.0	0.18-0.28	≤0.50	0.40	0.30	0.20	margin

2.2 Experimental Methods

Milling experiments were conducted on ultrasonic rolling-strengthened 7075-T6 aluminum alloy specimens using a Mitsubishi MV820 CNC machine tool. A four-flute SiC-coated cemented carbide end mill with a diameter of 6 mm was used as the cutting tool. During the cutting process, a three-component dynamometer was employed to acquire cutting force signals in real time to analyze the cutting force behavior of the material under different cutting parameters. The milling forces in the X, Y, and Z directions were recorded, as shown in Fig. 1(a). After machining, the three-dimensional surface morphology of the machined specimens was characterized using a VT6100 confocal microscope, as shown in Fig. 1(b). By obtaining the three-dimensional morphology characteristics of the machined surfaces under different cutting parameters, typical surface damage features, including grooves, scratches, material adhesion, localized tearing, and burrs, were analyzed. The machined surface quality was further evaluated in combination with surface roughness parameters.

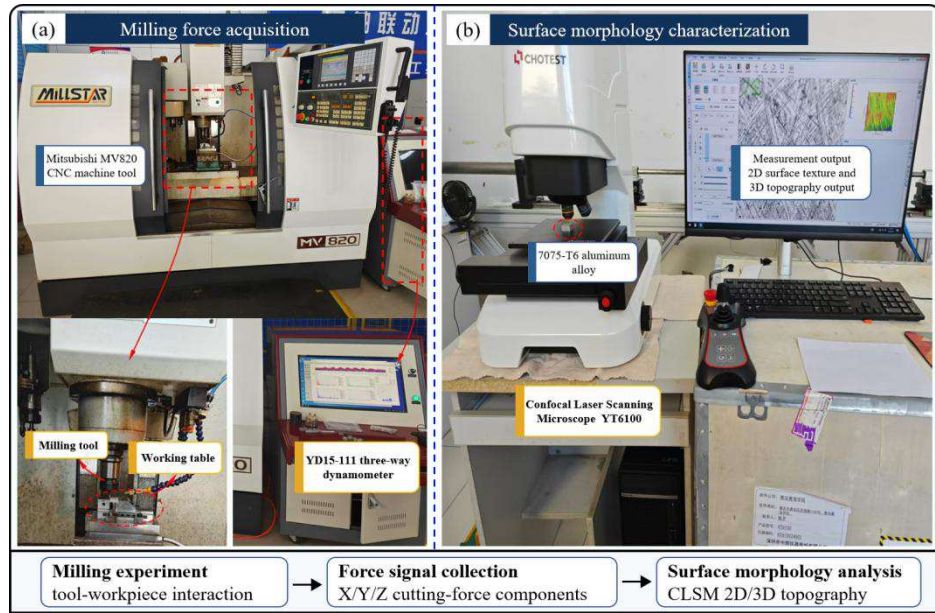


Fig. 1. Experimental equipment: (a) MV820 CNC machining center; (b) VT6100 confocal microscope

To investigate the effects of cutting parameters on the machining performance and surface damage behavior of ultrasonic rolling-strengthened 7075-T6 aluminum alloy, ultrasonic vibration frequency, cutting speed, depth of cut, and feed rate were selected as the main process parameters. A single-factor experimental method was adopted for the experimental design. The ultrasonic vibration frequencies were set as 0, 20, and 40 kHz; the cutting speeds (v_c) were 800, 1000, and 1200 mm/s; the depth of cut (a_p) was fixed at 15 μm ; and the feed rate (f) was fixed at 0.03 mm/r. The specific experimental parameters are listed in Table 2.

Table2 Single-factor experimental scheme for milling tests

No.	F/KHz	$V_c/\text{mm/s}$	$a_p/\mu\text{m}$	$f/\text{mm/r}$
BM	0	800		
BM	0	1000	15	0.03
BM	0	1200		
URS-20	20	800		
URS-20	20	1000	15	0.03
URS-20	20	1200		
URS-40	40	800		
URS-40	40	1000	15	0.03
URS-40	40	1200		

2.3 Simulation Model of Ultrasonic Rolling Strengthening and Cutting

To analyze the effect of ultrasonic rolling strengthening on the subsequent milling behavior of 7075-T6 aluminum alloy, an ultrasonic rolling strengthening simulation model and a post-strengthening cutting simulation model were established separately using ABAQUS finite element software. The ultrasonic rolling strengthening simulation model is shown in Fig. 2(a). In this model, two ultrasonic vibration rollers were set to contact the upper and lower surfaces of the workpiece. The upper and lower rollers were defined to rotate counterclockwise and clockwise, respectively, to simulate the continuous compression and plastic deformation of the workpiece surface during the actual rolling process. The workpiece moved horizontally to the right at a speed of 10 mm/s, and the ultrasonic vibration frequencies of the rollers were set as 0, 20, and 40 kHz to compare the surface deformation and stress distribution characteristics of the material under different ultrasonic vibration conditions.

Based on the ultrasonic rolling strengthening simulation, a subsequent milling simulation model of the strengthened 7075-T6 aluminum alloy was further established, as shown in Fig. 2(b). In the cutting simulation, a fully constrained boundary condition was applied to the bottom of the workpiece to restrict its overall displacement and rotation. The cutting tool was defined as a rigid body to simulate the shear removal of the workpiece material during the milling process.

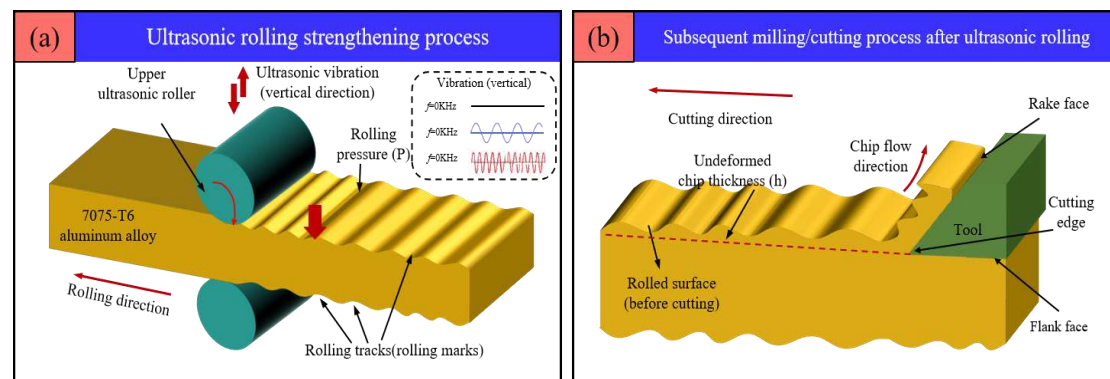


Fig. 2. Finite element simulation models: (a) ultrasonic rolling strengthening treatment; (b) milling model of ultrasonic rolling-strengthened 7075-T6 aluminum alloy

During the cutting process of ultrasonic rolling-strengthened 7075-T6 aluminum alloy, the high-speed contact, compression, and shearing between the cutting tool and the workpiece generate considerable cutting heat in the machining zone ^[15,16], resulting in a rapid temperature rise in the tool-chip contact region and the primary deformation zone. Meanwhile, pronounced stress concentration occurs near the cutting edge, causing the local material to rapidly reach the

yield state and undergo severe plastic deformation under the combined effects of high strain rate and thermo-mechanical coupling ^[17]. Therefore, in the cutting simulation, it is necessary to adopt a material constitutive model that can simultaneously describe strain hardening, strain-rate strengthening, and thermal softening effects ^[18]. The Johnson-Cook constitutive model can effectively characterize the flow stress evolution of metallic materials under high-speed cutting, high strain-rate, and elevated-temperature conditions ^[19]. Accordingly, the Johnson–Cook constitutive equation was used in this study to describe the thermo-mechanical coupled deformation behavior of 7075-T6 aluminum alloy during milling, and its expression is given as follows:

$$\sigma = (A + B\varepsilon^n)(1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})[1 - (\frac{T - T_0}{T_m - T_0})^m]$$

where σ is the equivalent stress; A is the initial yield strength; B is the material hardening modulus; ε is the equivalent plastic strain; n is the strain hardening exponent; C is the strain-rate sensitivity coefficient; $\dot{\varepsilon}$ is the current strain rate; $\dot{\varepsilon}_0$ is the reference strain rate; T_0 is the reference temperature; T_m is the melting temperature of the material; and m is the thermal softening coefficient. The above parameters ^[20] are listed in Table 3.

Table 3 Johnson-Cook model material parameters of 7075-T6 aluminum alloy

Material	A/Mpa	B/Mpa	n	m	C
7075-T6aluminum alloy	527	575	0.72	1.61	0.017

2.4 Simulation Verification

To verify the reliability of the established cutting simulation model for ultrasonic rolling-strengthened 7075-T6 aluminum alloy, the experimental and simulated values under different cutting speeds at the 0 kHz rolling condition were selected for comparative analysis, as shown in Fig. 3. It can be seen that, with increasing cutting speed, the simulated results of the three-directional cutting forces are generally consistent with the experimental results, indicating that the established model can effectively reflect the variation in cutting force during the cutting process. When the cutting speed was 1200 mm/s, the relative error of the Y-direction cutting force reached the maximum value of 16.64%, while the errors under the other conditions were generally controlled at approximately 15%, which is within the acceptable range for engineering simulation.

These results indicate that the ultrasonic rolling–cutting simulation model established based on the single-factor experiments has good prediction accuracy and can reliably simulate the material removal behavior and cutting force response of 7075-T6 aluminum alloy under different milling parameters.

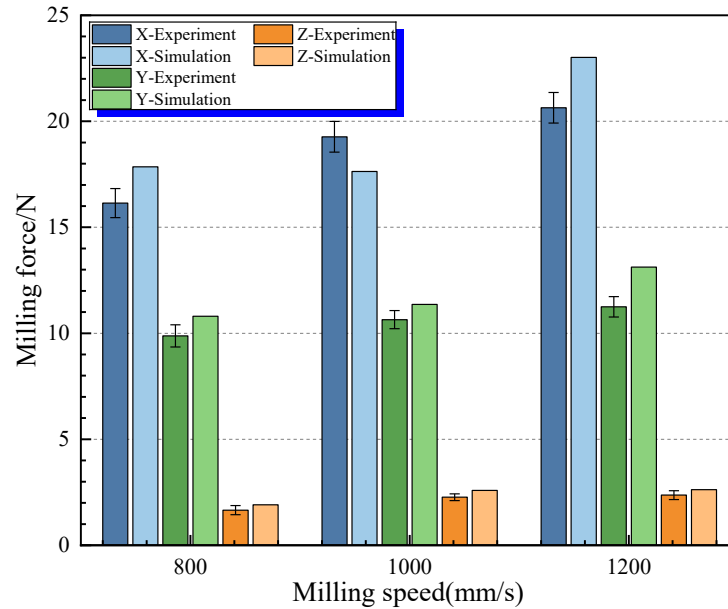


Fig.3 Comparison of experimental and simulated milling forces in the X, Y, and Z directions for 7075-T6 aluminum alloy

3. Results and Discussion

3.1 Cutting Force Analysis

Fig. 4 shows the variation in the three-directional cutting forces during the cutting of 7075-T6 aluminum alloy under different ultrasonic frequencies and cutting speeds. As shown in Fig. 4, the cutting forces in the X, Y, and Z directions all increased with increasing cutting speed under different ultrasonic frequency conditions, indicating that increasing the cutting speed enhanced the material removal resistance in the main cutting direction. It can also be observed that, at the same cutting speed, the cutting forces in the X, Y, and Z directions generally followed the order of 0 kHz > 20 kHz > 40 kHz, suggesting that increasing the ultrasonic frequency can effectively reduce the main cutting force. When the cutting speed increased from 800 to 1200 mm/s, the X-direction cutting forces under 0, 20, and 40 kHz increased by 1.09, 4.34, and 4.50 N, corresponding to increases of 7.88%, 30.50%, and 27.93%, respectively. The Y-direction milling forces increased by 1.44, 1.88, and 1.35 N, with corresponding increases of 20.21%, 21.35%, and 13.62%, respectively. The Z-direction milling forces increased by 0.74, 0.44, and 0.71 N,

corresponding to increases of 73.65%, 39.56%, and 42.86%, respectively.

These results indicate that the cutting speed and ultrasonic rolling frequency jointly affect the force state during the milling of 7075-T6 aluminum alloy. With increasing cutting speed, the volume of material removed per unit time by the cutting tool increases, and the shear deformation and plastic flow of the material ahead of the cutting edge become more intense ^[21]. Meanwhile, the friction at the tool–chip and tool–workpiece interfaces is enhanced, resulting in an increase in the cutting forces in all three directions. Among them, the X-direction cutting force mainly reflects the material shear removal resistance in the main cutting direction, and is therefore closely related to the material removal volume and the degree of shear deformation ^[22]. The Y-direction cutting force is mainly derived from radial extrusion and lateral friction of the cutting tool, and is strongly affected by the contact state between the side cutting edge and the machined surface ^[23]. The Z-direction cutting force mainly reflects the indentation, extrusion, and normal deformation effects of the cutting tool on the surface layer of the material, and is therefore more sensitive to the surface hardening state and elastic recovery behavior ^[24].

From the perspective of the effect of ultrasonic rolling frequency, the three-directional cutting forces decreased overall as the ultrasonic frequency increased from 0 kHz to 20 and 40 kHz, indicating that ultrasonic rolling strengthening can improve the interfacial contact state during subsequent milling. This is mainly because the combined action of high-frequency vibration and rolling-induced plastic deformation during ultrasonic rolling strengthening forms a relatively uniform plastic deformation layer on the material surface, and reduces the continuous adhesion and frictional resistance between the cutting tool and the workpiece to some extent. Compared with the 0 kHz condition, the interfacial resistance experienced by the cutting tool during cutting was reduced under the 20 and 40 kHz conditions, and the material removal process became more stable. Therefore, both the X-direction main cutting force and the Y-direction radial force were reduced.

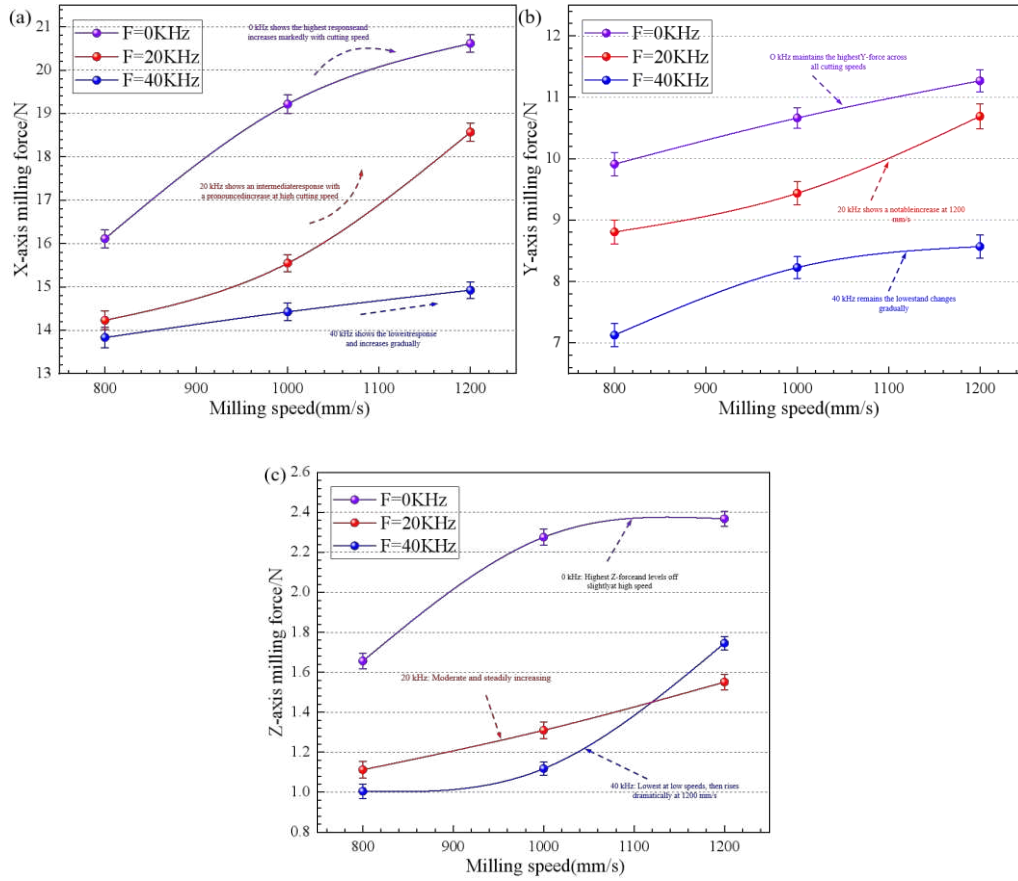


Fig. 4. Effect of cutting speed on milling forces in the X, Y, and Z directions under different ultrasonic rolling conditions

3.2 Residual Stress Analysis

Fig. 5 shows the variation in residual stress and the corresponding stress contour maps during the cutting of 7075-T6 aluminum alloy under different ultrasonic frequencies and cutting speeds. It can be seen that significant compressive residual stress was formed in the surface layer of the specimens under the ultrasonic rolling conditions of 0, 20, and 40 kHz. The compressive residual stress first increased and then decreased with increasing depth, eventually tending to stabilize. The compressive residual stress near the machined surface was relatively low. As the depth increased, the compressive residual stress gradually increased and reached its maximum value within approximately 5-13 μm from the surface. With further extension into the substrate, the compressive residual stress gradually decreased and became stable. This indicates that the extrusion, shearing, and frictional effects of the cutting tool on the workpiece surface during cutting were mainly concentrated in the near-surface region, resulting in severe plastic deformation and stress redistribution in this region.

Under the same ultrasonic frequency condition, as the cutting speed increased from 800 mm/s to 1000 and 1200 mm/s, the maximum compressive residual stress generally decreased. At a lower cutting speed, the contact time between the cutting tool and the workpiece was relatively longer, and the mechanical extrusion and shearing effects were more sufficient, which was conducive to the formation of a higher level of compressive residual stress in the surface and subsurface layers. However, with increasing cutting speed, the contact time between the cutting tool and the material was shortened, and the mechanical extrusion effect was relatively weakened. Meanwhile, the accumulation of cutting heat was intensified, and the thermal softening effect and stress release became more pronounced, resulting in a decrease in the surface compressive residual stress.

Under different ultrasonic rolling frequency conditions, the surface compressive residual stress levels of the specimens treated at 20 and 40 kHz were generally higher than those under the 0 kHz condition, indicating that ultrasonic vibration-assisted rolling can enhance the degree of plastic deformation in the surface layer and improve the surface strengthening effect. This is mainly because the coupled action of ultrasonic vibration and rolling load can promote grain refinement, dislocation multiplication, and microstructural densification in the surface layer, thereby forming a higher degree of work hardening and a greater compressive residual stress reserve [25,26]. Compared with the 0 kHz condition, the ultrasonic rolling-strengthened material could still maintain a significant compressive residual stress distribution during the subsequent cutting process.

Moreover, under the 40 kHz condition, the attenuation degree of compressive residual stress with increasing cutting speed was relatively small, indicating that the strengthened layer formed by higher-frequency ultrasonic rolling had stronger resistance to stress release. This is mainly associated with the more uniform plastic deformation and denser microstructure of the surface layer induced by high-frequency ultrasonic vibration. High-frequency vibration can reduce surface microdefects and local stress concentration [27], making the strengthened layer less prone to rapid stress relaxation under the thermo-mechanical coupling effect during milling. In contrast, under the 0 and 20 kHz conditions, the microstructural uniformity of the surface layer and the stability of the strengthened layer were relatively weaker. During high-speed milling, these layers were more easily affected by cutting heat, shear deformation, and friction, leading to more pronounced release of compressive residual stress.

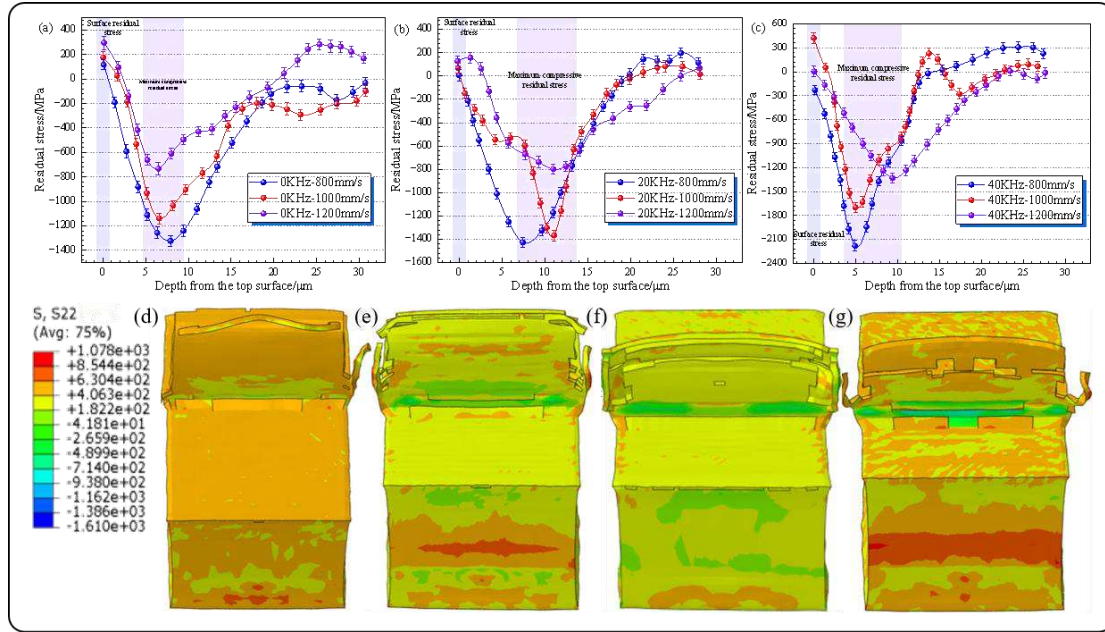


Fig. 5. Effect of cutting speed on residual stress distribution under ultrasonic rolling conditions

3.3 Surface Quality Analysis

Fig. 6 shows the variation in the surface roughness of 7075-T6 aluminum alloy under different ultrasonic frequencies and cutting speeds. It can be seen that, at the same cutting speed, the surface roughness of the milled 7075-T6 aluminum alloy generally followed the order of 0 kHz > 20 kHz > 40 kHz. This indicates that the surface roughness decreased with increasing ultrasonic frequency, and a higher ultrasonic frequency was more favorable for obtaining better machined surface quality. When the ultrasonic frequency was 0 kHz, the surface roughness of the specimen first decreased and then increased with increasing cutting speed. When the cutting speed increased to 1200 mm/s, the surface roughness reached the maximum value of 0.799 μm . Under the 20 kHz condition, the surface roughness also first decreased and then increased, reaching the minimum value of approximately 0.481 μm at a cutting speed of 1000 mm/s, while the values at 800 and 1200 mm/s were approximately 0.561 and 0.557 μm , respectively. When the ultrasonic frequency increased to 40 kHz, a negative correlation was observed between the surface roughness of 7075-T6 aluminum alloy and the cutting speed. The lowest surface roughness of 0.411 μm was obtained at a cutting speed of 1200 mm/s.

These results indicate that both cutting speed and ultrasonic frequency affect the machined surface quality of 7075-T6 aluminum alloy, and the surface roughness is more sensitive to changes in cutting speed under higher ultrasonic frequency conditions. This can be attributed to the fact

that, without ultrasonic vibration, the continuous contact, friction, and adhesion between the cutting tool and the workpiece are relatively strong, which easily induces surface defects such as grooves, material pile-up, and localized tearing, resulting in higher surface roughness. With increasing ultrasonic frequency, a relatively uniform strengthened layer is formed on the material surface through high-frequency plastic deformation, which can weaken the friction and adhesion between the cutting tool and the workpiece during cutting and make the material removal process more stable. Therefore, the lowest surface roughness of 7075-T6 aluminum alloy was obtained under the higher-frequency ultrasonic rolling condition, indicating that a higher ultrasonic frequency is beneficial for suppressing surface damage and improving machined surface quality.

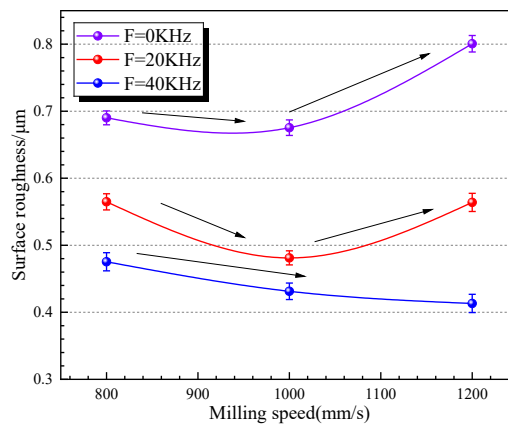


Fig. 6. Effect of cutting speed on surface roughness under different ultrasonic rolling conditions

Fig. 7 presents the surface morphologies of 7075-T6 aluminum alloy under different ultrasonic frequencies and cutting speeds. It can be seen that the specimen surfaces under different machining conditions exhibited tool marks, grooves, and material plastic flow features to varying degrees, indicating that the cutting tool exerted significant extrusion, ploughing, and shearing effects on the workpiece surface during cutting. Under the 0 kHz condition, as the cutting speed increased from 800 to 1200 mm/s, the machined surface gradually changed from relatively uniform oblique tool marks to more pronounced intersecting grooves and local undulations. In particular, at 1200 mm/s, the surface grooves became deeper, and local material pile-up and scratch features became more prominent. Under the 20 kHz condition, distinct intersecting tool marks were observed at 800 and 1200 mm/s, and obvious ploughing traces and material flow features appeared in local regions. In contrast, when the cutting speed was 1000 mm/s, the surface morphology became more uniform, with fewer deep grooves and less large-scale material pile-up,

and the degree of surface fluctuation was reduced. Under the 40 kHz condition, relatively obvious intersecting grooves and plastic deformation traces could still be observed at 800 and 1000 mm/s, whereas at 1200 mm/s, the machined surface exhibited a more uniform and finer texture, with a significant reduction in the size of surface defects. This indicates that the material removal process became relatively stable under the coupled action of high cutting speed and high-frequency ultrasonic rolling.

This phenomenon can be attributed to the fact that, under the 0 kHz condition without ultrasonic vibration, the interaction between the cutting tool and the workpiece was dominated by continuous contact and mechanical shearing. During cutting, the interfacial friction and adhesion were relatively strong, and the material was prone to extrusion accumulation and non-uniform plastic flow in front of the cutting tool. As a result, pronounced grooves, scratches, and localized tearing were more likely to form on the machined surface. With increasing cutting speed, the material removal rate per unit time increased, and the effects of cutting heat and strain rate became more significant. Consequently, the shearing and ploughing actions of the cutting tool on the material surface were intensified, aggravating surface damage under the 0 kHz condition.

For the specimens treated at 20 and 40 kHz, the combined effects of high-frequency vibration and rolling strengthening altered the microstructural state and mechanical response of the material surface, giving the surface layer a higher degree of hardening and more pronounced plastic deformation characteristics [28,29]. On the one hand, the strengthened layer improved the resistance of the material surface to tool indentation and ploughing, which helped reduce local material adhesion and large-scale tearing. On the other hand, when the cutting speed was low or moderate, the frictional extrusion between the strengthened layer and the cutting tool could still induce intersecting tool marks and local grooves. As the cutting speed further increased to 1200 mm/s, the shearing removal of the material during cutting became more continuous and stable. Combined with the surface strengthening effect induced by ultrasonic rolling, this resulted in a finer and more uniform machined surface texture, accompanied by reductions in large-scale grooves and material pile-up.

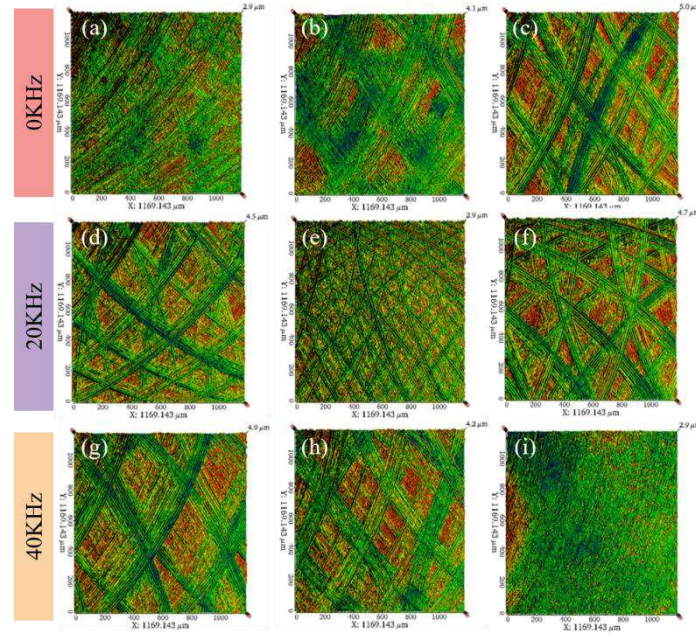


Fig. 7. Effect of cutting speed on the surface morphology of 7075-T6 aluminum alloy under different ultrasonic rolling conditions

3.4 Synergistic Mechanism between Ultrasonic Rolling Strengthening and Cutting and Its Effect on the Performance of 7075-T6 Aluminum Alloy

To further reveal the machining response mechanism of ultrasonic rolling-strengthened 7075-T6 aluminum alloy during milling, the synergistic interaction between the ultrasonic rolling-strengthened layer and the subsequent milling process was discussed based on the results of cutting force, surface roughness, surface morphology, and residual stress. During ultrasonic rolling strengthening, the roller periodically contacts the workpiece surface under the combined action of static pressure, rolling action, and high-frequency ultrasonic vibration, resulting in severe plastic deformation in the near-surface region. This process promotes surface grain refinement, increases dislocation density, and introduces a compressive residual stress field into the surface and subsurface layers, thereby forming a strengthened layer characterized by hardness, microstructural, and stress gradients. Compared with the 0 kHz condition, ultrasonic rolling strengthening at 20 and 40 kHz can significantly alter the mechanical response of the surface layer of 7075-T6 aluminum alloy, resulting in changes in the tool-workpiece contact state, material removal mode, and surface damage behavior during subsequent cutting.

During cutting, the cutting edge imposes shearing, extrusion, and frictional effects on the ultrasonic rolling-strengthened layer, causing local material removal, plastic flow, and stress

redistribution under the tool load. On the one hand, the surface strengthened layer formed by ultrasonic rolling strengthening improves the resistance of the material to tool indentation and ploughing, thereby reducing the tendency for material adhesion, surface tearing, and local pile-up to some extent. On the other hand, the increased hardness and compressive residual stress of the strengthened layer also modify the shear deformation behavior of the material during cutting, making the cutting force, surface roughness, and residual stress highly sensitive to cutting speed. With increasing cutting speed, the material removal volume per unit time increases, the friction at the tool–chip and tool-workpiece interfaces is intensified, and more cutting heat is generated in the machining zone. These effects promote thermal softening, stress release, and local plastic deformation in the surface layer ^[30]. Therefore, increasing cutting speed generally leads to higher three-directional cutting forces and weakens the retention capability of compressive residual stress in the milled surface layer.

The effect of ultrasonic rolling frequency on the cutting response is mainly reflected in two aspects. First, high-frequency ultrasonic vibration can enhance surface plastic deformation during rolling, leading to more pronounced grain refinement and work hardening effects in the surface layer, and thus improving the integrity and deformation resistance of the strengthened layer. Second, the micro-undulation and microstructural homogenization effects induced by ultrasonic vibration can modify the contact state between the cutting tool and the workpiece surface, weaken continuous friction and adhesion during milling, and thereby reduce cutting resistance while improving the stability of material removal ^[31]. However, when the ultrasonic frequency is excessively high, the hardness and elastic recovery capacity of the strengthened layer are further enhanced. In this case, the cutting tool needs to overcome greater indentation resistance and rebound resistance in the normal direction ^[32,33], which may lead to an increasing tendency in the Z-direction cutting force and surface roughness.

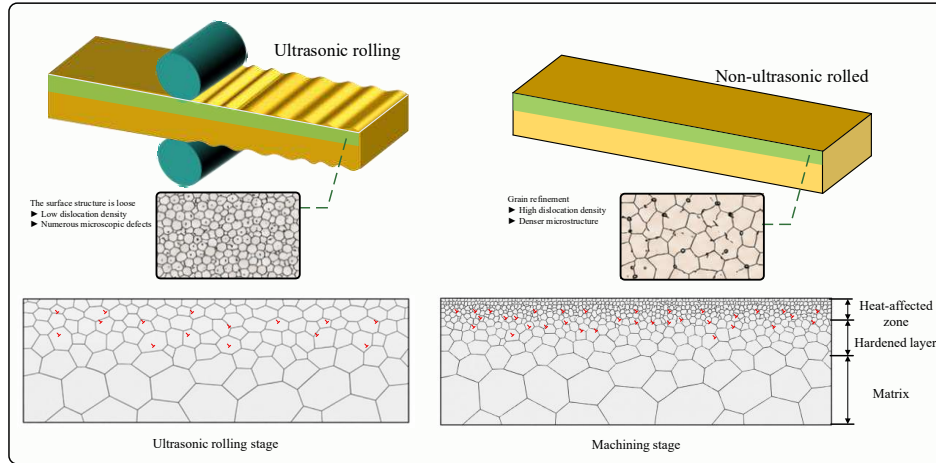


Fig. 8. Schematic illustration of the interaction mechanism between the ultrasonic rolling-strengthened layer and the cutting process

4 Conclusions

In this study, ultrasonic rolling-strengthened 7075-T6 aluminum alloy was selected as the research object, and the cutting behavior under different ultrasonic frequencies and cutting speeds was investigated. The effects of the ultrasonic rolling-strengthened layer on the subsequent machining performance and surface damage behavior were systematically analyzed. The main conclusions are as follows:

(1) Cutting speed and ultrasonic frequency jointly affected the force state during the cutting of 7075-T6 aluminum alloy. As the cutting speed increased from 800 to 1200 mm/s, the three-directional cutting forces generally increased under the 0, 20, and 40 kHz conditions, indicating that increasing cutting speed enhanced shear deformation, extrusion, and interfacial friction during material removal. At the same cutting speed, the three-directional cutting forces generally followed the order of 0 kHz > 20 kHz > 40 kHz, indicating that increasing the ultrasonic rolling frequency improved the tool–workpiece interfacial contact state, reduced cutting resistance, and made the material removal process more stable.

(2) Ultrasonic rolling strengthening significantly affected the residual stress distribution in the surface layer after milling. Under different ultrasonic frequency conditions, obvious compressive residual stress was formed in the specimen surface layer. Along the depth direction, the compressive residual stress first increased and then decreased, gradually tending to stabilize. The maximum compressive residual stress was mainly distributed within 5–13 μm from the surface. With increasing cutting speed, the maximum compressive residual stress generally

decreased, indicating that cutting heat accumulation and stress release were enhanced under high-speed cutting conditions. In contrast, the specimens treated by ultrasonic rolling strengthening at 20 and 40 kHz exhibited higher compressive residual stress levels than those under the 0 kHz condition, suggesting that ultrasonic rolling strengthening was beneficial for improving the surface strengthening effect and the retention capability of compressive residual stress.

(3) Increasing ultrasonic rolling frequency was beneficial for improving the machined surface quality of 7075-T6 aluminum alloy and suppressing surface damage. As the ultrasonic frequency increased from 0 to 40 kHz, the surface roughness after milling generally decreased. The lowest surface roughness of 0.411 μm was obtained under the 40 kHz and 1200 mm/s condition. The surface morphology results showed that obvious defects, such as grooves, material pile-up, and localized tearing, were more likely to occur on the machined surface without ultrasonic vibration. After high-frequency ultrasonic rolling strengthening, the surface texture became finer and more uniform, and the degree of surface damage was significantly reduced. Overall, ultrasonic rolling strengthening improved the stability of material removal and the interfacial friction state during subsequent cutting by introducing surface plastic deformation, work hardening, and compressive residual stress, thereby enhancing the machined surface quality of 7075-T6 aluminum alloy.

References

- [1]Tushar S ,Visvalingam B ,Sudersanan M .Mitigation of heat treatment distortion of AA 7075 aluminum alloy by deep cryogenic processing using the Navy C-ring test[J].Materials Testing,2021,63(8):758-763.
- [2]Wei W ,Jie S ,Weijun L , et al.Effect of laser energy density on surface physical characteristics and corrosion resistance of 7075 aluminum alloy in laser cleaning[J].Optics and Laser Technology,2022,148.
- [3]Li J ,Song R ,Qi X , et al.Effects of polyvinylidene fluoride sealing on micro-arc oxidation coating of 7075 aluminum alloy[J].Anti - Corrosion Methods and Materials,2022,69(1):1-8.
- [4]Yu D P ,Maitri K ,Navneet K , et al.Review of improvement of machinability and surface integrity in machining on aluminum alloys[J].The International Journal of Advanced Manufacturing Technology,2023,129(11-12):4743-4779.
- [5]Zhang P ,Cao X ,Zhang X , et al.Machinability and cutting force modeling of 7055 aluminum

alloy with wide temperature range based on dry cutting[J].The International Journal of Advanced Manufacturing Technology,2020,111(prepublish):2787-2808.

[6]Béjar M S ,Trujillo F ,Bañón F , et al.Predictive tool path compensation using ANN to minimize slenderness-induced errors in dry turning of UNS A97075-T6[J].Journal of Manufacturing Processes,2026,169365-378.

[7]Yang C ,Li Y ,Ge T , et al.Distortion suppression mechanism of laser directed energy deposition on thin sheets based on ultrasonic rolling prestressing[J].Journal of Materials Processing Tech.,2025,345119051-119051.

[8]Yi-Xin L ,Cheng-Cheng Z ,Run-Zi W , et al.Quantitative evaluations of improved surface integrity in ultrasonic rolling process for selective laser melted in-situ TiB2/Al composite[J].Journal of Manufacturing Processes,2022,77412-425.

[9]Yang T ,Chen J ,Chen S , et al.Prediction of residual stress field of ultrasonic rolling processed 20CrNiMo based on physics-informed neural networks[J].Journal of Manufacturing Processes,2025,149841-851.

[10]Bayram S B ,Yavuzyeğit B ,Kabakçı O M , et al.Multi-Criteria Evaluation of Cryogenic Holding Time Effects on AA7075-T6 Milling Performance[J].International Journal of Precision Engineering and Manufacturing,2026,(prepublish):1-30.

[11]Ping Z ,Yeran G ,Shunxiang W , et al.Effect of T6I4 and T6I6 on the machinability of 7075 aluminum alloy and tool wear mechanism[J].The International Journal of Advanced Manufacturing Technology,2023,127(9-10):4453-4471.

[12]Hongwan J ,Zhongwei R ,Zhongfei Z , et al.Reinforcement effect of cutting process on machined surface quality and performance of aviation aluminum alloy 7075 based on Oxley-Welsh theory[J].Journal of Manufacturing Processes,2023,9538-52.

[13]Jianxin Z ,Yingju S ,Yonglei G , et al.Analytical model of residual stress in ultrasonic rolling of 7075 aluminum alloy[J].Journal of Manufacturing Processes,2022,80132-140.

[14]Zhiwei P ,Shuaixing W ,Xiaole Y , et al.Effect of spindle speed during ultrasonic rolling on surface integrity and fatigue performance of Ti6Al4V alloy[J].International Journal of Fatigue,2022,(prepublish):106794-.

[15]Wang D ,Han A ,Han J , et al.Machining-Induced Surface Integrity Enhancement of Ti-6Al-4V Titanium Alloy via Ultrasonic Vibration Side Milling Under High-Speed Machining

and Dry Conditions[J].Coatings,2025,15(6):662-662.

[16]Yang K ,Cao Z ,Zhao X , et al.Experimental Study of Micro-Milling Carbon Fibre Reinforced Composites Under Variable Cooling And Lubrication Strategies[J].International Journal of Precision Engineering and Manufacturing-Green Technology,2024,12(4):1-14.

[17]Palanivel R ,Dinaharan I ,Selvam R D J , et al.Microstructure and mechanical properties of the near surface of titanium alloy Ti-6Al-4V machined by micro-textured tools[J].The International Journal of Advanced Manufacturing Technology,2026,143(9-10):1-14.

[18]Fan T ,Wang Y ,Tan L , et al.Development of a macro – micro coupled constitutive model with hierarchical parameter identification for γ -TiAl alloy machining[J].Journal of Manufacturing Processes,2026,169422-443.

[19]Li M ,Li Q ,Pan X , et al.Progress and prospects in cutting of particle reinforced metal matrix composites[J].Composite Structures,2025,372119598-119598.

[20]Silva D F ,Franzão H ,Outeiro J .Prediction of the energy consumption and surface integrity in machining of Inconel 718 superalloy using an orthogonal cutting model considering the stress state[J].Journal of Manufacturing Processes,2025,14982-97.

[21]Sahu S T ,Sahu K R ,Krishna P , et al.Tribological performance of self-lubricating micro textured tools in sustainable machining of Ti-6Al-4V[J].Wear,2026,600206807-206807.

[22]Ping Z ,Shunxiang W ,Zhenyong L , et al.Investigation on the mechanism of micro-milling CoCrFeNiAlX high entropy alloys with end milling cutters[J].Vacuum,2023,211.

[23]Ren T ,Yu J ,Deng L , et al.Triaxial cutting force prediction model for disc cutters based on full-scale rotary cutting tests of composite rock strata[J].International Journal of Rock Mechanics and Mining Sciences,2026,202106517-106517.

[24]Branislav S ,Djordje C ,Stevo B , et al.Optimization of superalloy Inconel 718 micro-milling process by combined Taguchi and multi-criteria decision making method[J].Journal of the Brazilian Society of Mechanical Sciences and Engineering,2024,46(7).

[25]Feng S ,Feng P ,Feng F , et al.Analytical-numerical coupled model for residual stress prediction on complex geometric surfaces under multi-pass ultrasonic rolling[J].Journal of Manufacturing Processes,2026,17030-46.

[26]Li G ,Zhang F ,Hong B , et al.Study on surface properties of titanium alloy after pulsed current and pulsed magnetic field coupling assisted ultrasonic

rolling[J].Wear,2026,594206663-206663.

[27]Li T ,Meng Y ,Dong X , et al.Fabrication of micro-nano composite textures on joint implant surfaces and their bio-tribological performance[J].Surfaces and Interfaces,2025,73107497-107497.

[28]Ma G X ,Yan C ,Lian J J , et al.Unraveling surface microtexture evolution mechanism of austenitic stainless steel thin strip during asymmetric rolling by crystal plasticity modeling[J].Journal of Iron and Steel Research International,2026,33(7):196-196.

[29]Boxin Y ,Shuangmin L ,Congpeng S , et al.A size-dependent closure criterion for slab corner defects during vertical rolling process based on mathematical method[J].Ironmaking & Steelmaking,2026,53(5):963-977.

[30]Yu L ,Li S ,Yan P , et al.Effect of temperature and strain rate on compression properties of forged Al0.5CoCrFeNi high entropy alloy[J].Materials Science & Engineering A,2026,962150194-150194.

[31]Wei L ,Chen L ,Deng L , et al.Effect of differential speed rolling combined with non-isothermal aging on the microstructure and properties of 7075 aluminum alloy[J].Materials Characterization,2026,237116561-116561.

[32]Abbasabad A S ,Zadshakoyan M ,Oskui E A .Experimental and numerical investigation of equal channel angular rolling pass effects on mixed-mode (I/II) fracture behavior of 6061 aluminum alloy[J].Engineering Failure Analysis,2026,194110937-110937.

[33]Hajjaji I ,Ftoutou E ,Said B M , et al.Comparative study of milling for SS316L parts: WAAM-CMT versus rolled processes through vibration signal and surface roughness analysis[J].Journal of Mechanical Science and Technology,2026,40(2):1-10.

