

Effect of Surface Properties of Titanium Alloy under Ultrasonic Rolling Treatment

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Abstract: To address the issues of low surface hardness and poor anti-stick-slip wear performance exhibited by TC4 titanium alloy during service in aerospace and medical implant applications, this study employed ultrasonic surface rolling process technology for surface strengthening. The effects of key process parameters, such as the number of rolling passes, on surface microstructure, mechanical properties, and tribological behavior were systematically investigated. Characterization via scanning electron microscopy, X-ray diffraction, microhardness testing, residual stress analysis, and ball-on-disc friction wear tests revealed that USRP induces severe plastic deformation in the surface layer of TC4 titanium alloy, forming a nano- or submicron-scale refined layer with a gradient residual compressive stress field. As the number of rolling passes increases, surface microhardness first rises then declines, peaking at approximately 366.5 HV_{0.1} after 5 passes—a 24.2% increase over the untreated substrate (295 HV_{0.1}). The absolute residual compressive stress reaches its maximum value of approximately -850 MPa after 10 passes, slightly decreasing after 15 passes due to fatigue layer formation from overprocessing. Friction tests indicate that USRP treatment effectively reduces the initial friction coefficient during the running-in phase. While its impact on the average friction coefficient during the stable phase is limited, it significantly enhances the surface layer's deformation resistance through grain refinement and surface densification. Moderate USRP treatment achieves an optimal balance between grain refinement, residual compressive stress, and surface integrity, providing theoretical and process references for manufacturing high-performance surfaces in TC4 titanium alloys.

Keywords: TC4 titanium alloy, Ultrasonic rolling process, Surface strengthening, Grain refinement, Friction wear tests

1. Introduction

Ti-6Al-4V titanium alloy is widely used in aircraft engines, structural fasteners, and medical implants due to its high specific strength, excellent corrosion resistance, and biocompatibility [1-5]. However, its low hardness and poor anti-stick-slip wear performance limit its application in high-load friction environments. Traditional surface strengthening techniques, such as shot peening, ion nitriding, and laser cladding, can enhance surface strength to some extent. However, these processes are complex, costly, and prone to introducing surface defects [6-8].

Ultrasonic surface rolling processing (USRP) [9] combines the energy superposition effects of rolling plastic deformation and ultrasonic vibration, forming a dense ultrafine grain structure and a gradient residual compressive stress field in the material surface layer [10]. Zheng et al. [11] investigated how the surface layer induces stronger crystallographic rearrangement, forming high-density grain boundaries and dislocation configurations, achieving superior comprehensive surface properties compared to conventional surface rolling. Ma et al. [12] studied the fatigue properties of 45CrNiMoVA ultra-high-strength steel using secondary ultrasonic rolling treatment, revealing that USRP enhances resistance to fatigue crack initiation and propagation. Duan et al. [13] discovered that USRP effectively fractures and dissolves elongated primary carbides, forming a fine microstructure that suppresses crack initiation and propagation, thereby enhancing wear resistance; Li et al. [14] compared the effects of surface rolling and USRP on 2195 Al-Li alloy, demonstrating that USRP significantly reduced the average coefficient of friction due to its unique acoustic effects and dynamic recrystallization mechanism; Lei et al. [15] discovered that USRP can form gradient nanostructures on pure titanium surfaces, significantly enhancing material strength and plasticity. Overall, USRP technology demonstrates notable advantages

in improving metal surface properties ^[16], though further research is needed on its application effectiveness and potential limitations across different materials and operating conditions ^[17]. The aforementioned studies indicate that this technology can significantly reduce surface roughness and improve wear resistance in steel, magnesium alloys, and aluminum alloys. However, systematic investigations into the surface property evolution mechanism of TC4 titanium alloy under USRP remain scarce.

This paper focuses on TC4 titanium alloy to systematically investigate the influence of USRP processing cycles on its surface microstructure and mechanical properties. It reveals the surface strengthening mechanism of materials under ultrasonic rolling, providing theoretical and process references for the manufacturing of high-performance surfaces in titanium alloys.

2. Experimental Procedures and Results

2.1 Experimental Procedure

The experiment utilized TC4 titanium alloy plates in a heat-isostatic-pressed and annealed state (composition: Al 6.0%, V 4.0%, balance Ti), with an initial microhardness of 295 HV0.1. An USP-300 ultrasonic surface rolling device (frequency 20 kHz) was employed, featuring a rolling ball diameter of $\Phi 6$ mm and a ball head material of GCr15 cemented carbide. The experimental design is shown in Table 1 (Sample 1 is untreated):

Table 1 Experimental Design.

Sample	Static Pressure (N)	Rolling Passes	Feed Rate (mm/min)
Sample 2	100	1	0.1
Sample 3	100	3	0.1
Sample 4	100	5	0.1
Sample 5	100	10	0.1
Sample 6	100	15	0.1

The surface properties of TC4 titanium alloy after ultrasonic rolling treatment were systematically characterized using multiple testing methods. First, the surface morphology of the specimens was observed using scanning electron microscopy (SEM), combined with X-ray diffraction (XRD) to analyze phase transformations. Subsequently, microhardness distribution was measured at ten points horizontally using an HV-1000 microhardness tester under a load of 100 g and an indentation spacing of 30 μ m to analyze the hardened layer characteristics. Residual stress testing employed a μ -X360s X-ray residual stress analyzer with Cr-K α radiation, utilizing the $\sin^2\psi$ method to obtain surface compressive stress distribution. Additionally, wear performance testing was conducted on a ball-on-disc friction and wear tester. The friction pair consisted of a GCr15 steel ball operating under a load of 10 N and a single stroke of 8 mm, performing reciprocating linear motion. The primary evaluation metrics were the coefficient of friction and the morphology of the wear scar.

2.2 Experimental Results

2.2.1 Surface Morphology and Phase Transformation

As shown in Figure 1, the surface morphology evolution of the titanium alloy under different numbers of ultrasonic rolling treatments is clearly demonstrated. From Figure 1(a) to 1(f), the surface morphology undergoes a dynamic evolution process characterized by smoothness, emergence of defects, increased defects accompanied by grain refinement, reduced defects, and surface re-densification. Figure 1(a) represents the untreated state, featuring a relatively smooth surface with only minor machining scratches and no significant plastic deformation or defects. This serves as the material's original surface condition, providing a baseline for subsequent comparisons. Figures 1(b–c) show low-cycle treatments. As the number of processing cycles increases to 1, the surface begins to exhibit a small number of fine pits and pitting-like defects. When the number increases to 3, surface defects significantly increase and expand, forming distinct black spots and pitted areas. This indicates that in the initial stage, the impact action of ultrasonic rolling causes localized spalling and damage to the surface material. Figure 1(d) shows the medium-cycle treatment, where surface defect density peaks. Concurrently, the elliptical region reveals pronounced grain refinement. Sustained impact and shear forces fracture and refine surface grains, forming a nanometer- or submicron-scale grain layer. Figures 1(e-f) represent high-cycle treatments. When the number of processing cycles further increased to 10, the surface defect density paradoxically

decreased, and the overall surface became smoother and denser. This occurred because the pits and microcracks formed earlier were compacted during subsequent repeated rolling, reducing surface roughness and forming a dense work-hardened layer. This morphological evolution directly influences the material's surface properties: grain refinement enhances hardness and wear resistance, while excessive surface defects may serve as fatigue crack initiation sites, reducing fatigue life. Consequently, an optimal number of processing cycles exists to balance strengthening effects and surface integrity.

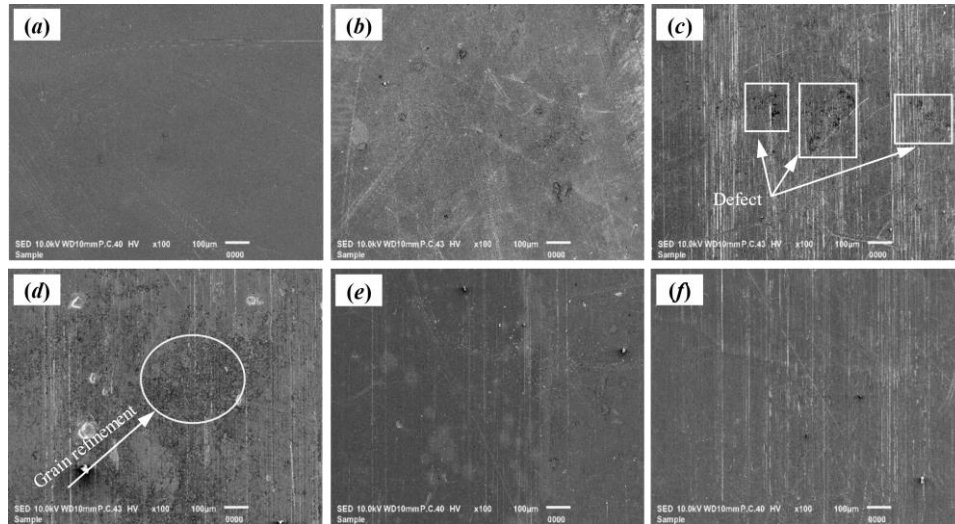


Figure 1 Scanning electron microscope images of titanium alloy surface topography: (a) Sample 1 untreated; (b) to (f) Samples 2–6 subjected to ultrasonic rolling treatment, with processing cycles of 1, 3, 5, 10, and 15, respectively.

Figure 2 reveals the effects of ultrasonic rolling treatment on the phase structure and crystallographic state of the titanium alloy. The two curves, derived from samples 1 and 4, are primarily composed of diffraction peaks characteristic of the hexagonal close-packed α -Ti structure. Simultaneously, a faint peak corresponding to the body-centered cubic β -Ti structure is observed around 38° , consistent with the typical phase composition of titanium alloys. Ultrasonic rolling did not introduce new phases, indicating that this process primarily alters the microstructure through plastic deformation rather than chemical reactions or phase transformations. The intensity of the main diffraction peaks in USRP-treated samples is significantly higher than in untreated samples. This intensity increase is not due to increased phase content but results from strong preferential orientation caused by the intense plastic deformation during ultrasonic rolling. Surface grains rotate under alternating stresses, aligning certain crystal planes parallel to the surface. This alignment manifests as heightened peak intensities in XRD analysis. Close observation reveals that diffraction peaks after USRP exhibit a certain degree of broadening, inversely proportional to grain size. This directly demonstrates that ultrasonic rolling significantly refines surface grains, forming a nanometer- or submicron-scale grain layer. This finding fully aligns with the “lattice refinement” phenomenon observed in the previously mentioned SEM images.

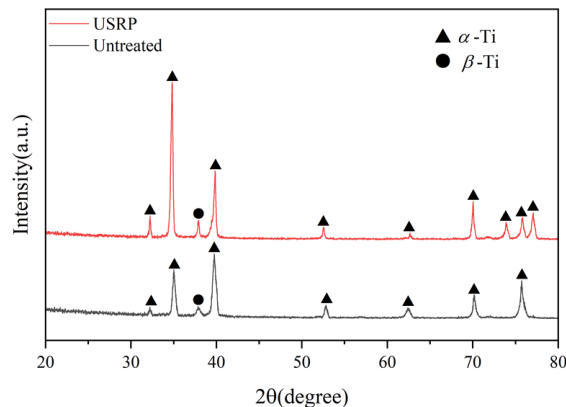


Figure 2 XRD patterns of USRP and untreated surfaces.

Figure 3 cross-sectional SEM images clearly demonstrate the profound impact of ultrasonic rolling treatment on the microstructure of the titanium alloy surface layer. Figure 3(a) shows the untreated cross-

section with a uniform microstructure, no obvious layered structure, and large grain size, representing the original matrix state of the material. Figures 3(b-c) depict low-cycle treatments, where after 1 and 3 cycles, a distinct refined layer formed on the outermost surface of the sample. This layer exhibits significant morphological differences from the matrix, characterized by intensely fragmented and refined grains displaying a dense equiaxed structure. The thickness of the refined layer progressively increases with the number of treatments. Figure 3(d) shows the intermediate treatment state. As the treatment count increases to 5, the refined layer thickens further, and its interface with the matrix becomes more distinct. Continuous plastic deformation progressively refines surface grains, creating a gradient structure that mitigates stress concentration and enhances material performance. Figures 3(e-f) illustrate high-cycle processing: beyond 10 cycles, surface fragmentation occurs. At 15 cycles, the refinement layer reaches maximum thickness, revealing an additional fatigue layer within. This indicates that excessive rolling introduces additional damage and microcracks into the surface layer, creating potential fatigue sources. It demonstrates that ultrasonic rolling possesses an optimal number of passes; beyond this threshold, the strengthening effect is counteracted by introduced defects, potentially degrading material performance.

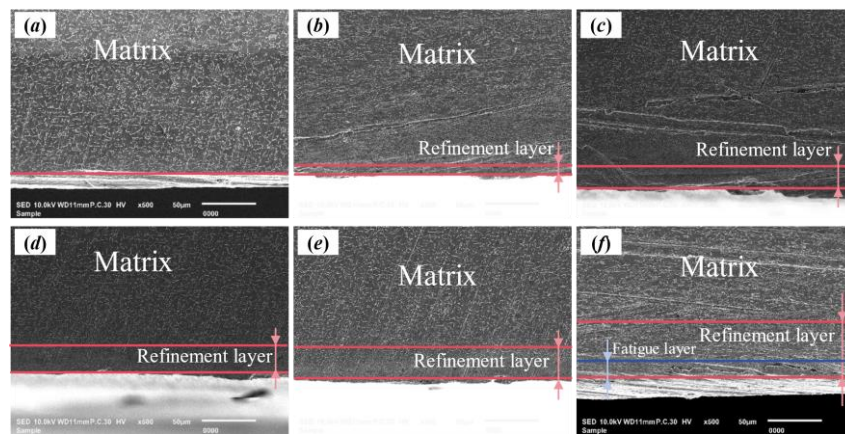


Figure 3 Scanning electron micrographs of titanium alloy cross-section morphology: (a) Sample 1 untreated; (b) to (f) Samples 2–6 subjected to ultrasonic rolling treatment, with processing cycles of 1, 3, 5, 10, and 15, respectively.

2.2.2 Microhardness and Hardened Layer Characteristics

As shown in Figure 4, the microhardness of the titanium alloy significantly increased after ultrasonic rolling treatment compared to the untreated sample.

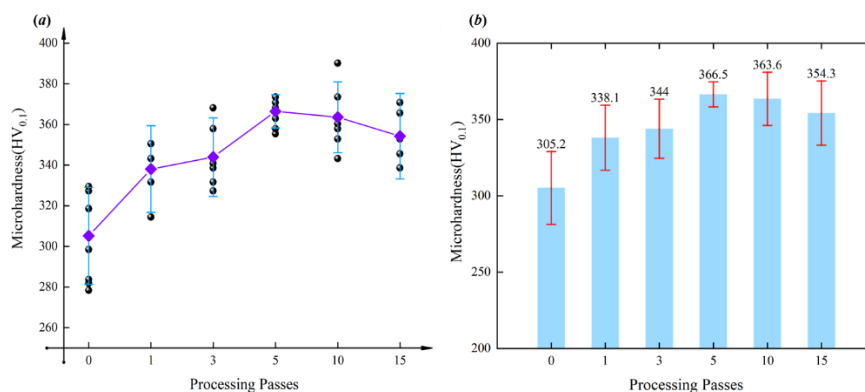


Figure 4 Effect of ultrasonic rolling treatment cycles on microhardness of titanium alloy: (a) Scatter plot of microhardness versus number of treatments; (b) Corresponding mean values and standard deviations.

Figure 4(a) displays multiple measurement values for each treatment cycle as scatter points, with a fitted line illustrating the overall hardness trend. Figure 4(b) provides a more intuitive comparison of average hardness values and data fluctuation ranges across different treatment cycles. In summary, hardness values increase with the number of treatments, reaching a maximum of approximately 366.5 HV_{0.1} after 5 USRP treatments, followed by slight decreases at 10 and 15 treatments. Intense plastic deformation refines surface grains and increases dislocation density, significantly enhancing the material's deformation resistance. The hardness increase is directly related to grain refinement and work

hardening. After exceeding five treatments, hardness declines due to microcracks and defects introduced by overprocessing, which partially offset the strengthening effects.

2.2.3 Residual Stress Distribution

As shown in Figure 5, the effect of USRP treatment on residual stresses in the surface layer of titanium alloys. Untreated samples exhibit tensile residual stresses of approximately 180 MPa, which originate from internal stresses generated during initial processing or heat treatment due to thermal expansion and contraction, as well as uneven microstructural transformations. The presence of tensile stresses acts as a fatigue crack initiation source, significantly reducing the material's fatigue life. Following USRP treatment, residual stress rapidly transforms from tensile to compressive stress, with its absolute value increasing with the number of treatment cycles. This compressive stress arises from the intense plastic deformation induced by ultrasonic rolling. It effectively counteracts tensile stresses generated by external loading, thereby suppressing the initiation and propagation of surface cracks. When the number of treatments increased to 10 and 15 cycles, the absolute value of residual compressive stress rose sharply, reaching very high levels. Although high residual compressive stress is beneficial for fatigue performance, excessive compressive stress may also cause microcracks or delamination within the material, thereby compromising its integrity. As shown in the figure, the absolute value of compressive stress after 15 treatments is slightly lower than that after 10 treatments. This may be attributed to partial stress release or microcrack initiation caused by overprocessing.

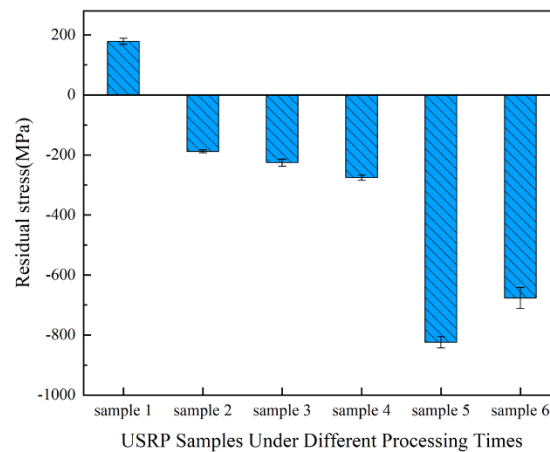


Figure 5 Residual stress analysis of titanium alloy at different USRP processing cycles.

2.2.4 Friction and Wear Properties

Based on the preceding optimal parameter investigation, untreated and USRP 5-treated samples were selected for friction and wear testing.

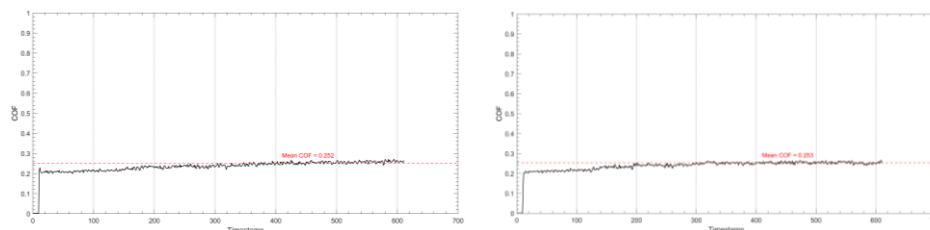


Figure 6 Residual stress analysis of titanium alloy at different USRP processing cycles:(a) Untreated surface; (b) USRP processing surface.

As shown in Figure 6, untreated and USRP 5-treated titanium alloy samples exhibited distinct tribological behavior differences across various stages during ball-on-disc friction and wear testing. During the initial running-in phase, the untreated surface exhibited an average coefficient of friction (COF) of approximately 0.235, whereas the USRP 5-treated sample achieved an initial COF reduced to about 0.200. This indicates that ultrasonic rolling effectively lowers the initial friction coefficient. This phenomenon can be attributed to the surface grain refinement and densification induced by ultrasonic rolling, which results in a more uniform distribution of surface asperities and consequently reduces initial contact stress. However, as the running-in process progressed, the original micro-asperities on the untreated surface were rapidly worn down, gradually increasing the actual contact area. Consequently,

the average coefficient of friction in the stable stage (0.252) converged toward that of the USRP-treated sample (0.253), exhibiting highly similar curve profiles and fluctuation characteristics. This indicates that under the experimental conditions, ultrasonic rolling has a limited effect on the stable friction coefficient. Its primary advantage lies in optimizing tribological performance during the initial stage rather than significantly reducing the long-term stable friction coefficient.

3. Conclusion

Under the combined action of high-frequency impact and hydrostatic pressure, USRP induces severe plastic deformation in the material surface layer, causing multi-stage grain refinement. Ultrasonic energy activates dislocation motion, promoting dislocation slip and the formation of cellular structures to create a strengthening gradient layer. This study systematically investigates the effects of USRP processing cycles on the surface microstructure, mechanical properties, and tribological behavior of TC4 titanium alloy, yielding the following conclusions:

(1) USRP treatment induces intense plastic deformation in the titanium alloy surface layer, significantly refining grains to form nano- or submicron-scale grain layers while generating strong preferential orientation. As processing cycles increase, the surface undergoes a dynamic evolution from defect accumulation to grain refinement, followed by surface re-densification. Overprocessing introduces fatigue layers within the refined layer, creating potential crack initiation sites, indicating the existence of an optimal processing window.

(2) USRP effectively induces residual compressive stress and significantly enhances surface microhardness. Hardness initially increases then decreases with processing cycles, peaking at approximately 366.5 HV_{0.1} after 5 treatments. The absolute value of residual compressive stress reaches its maximum of about -850 MPa after 10 treatments, slightly declining after 15 treatments—correlated with microcrack initiation and stress release due to overprocessing.

(3) Five USRP treatments effectively reduce the initial friction coefficient during the run-in phase from 0.235 to 0.200, but have limited impact on the average friction coefficient during the steady-state phase. This indicates that USRP's primary advantage lies in optimizing run-in performance rather than significantly altering long-term friction coefficients.

Overall, moderate USRP treatment (5–10 cycles) achieves an optimal balance between grain refinement, residual compressive stress, and surface integrity. This significantly enhances the surface hardness and fatigue resistance of titanium alloys, providing a viable surface strengthening approach for high-load applications in aerospace, biomedical, and other fields.

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