

Article

Machining-Induced Surface Integrity Enhancement of Ti-6Al-4V Titanium Alloy via Ultrasonic Vibration Side Milling Under High-Speed Machining and Dry Conditions

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Abstract: Ti-6Al-4V titanium alloy is widely used in aerospace and other fields due to its excellent performance, but conventional machining has problems such as high cutting force, high temperature, and tool wear, which leads to the difficulty of balancing surface quality and efficiency. Ultrasonic vibration-assisted machining can effectively improve machining performance. Although the cutting force and heat of ultrasonic vibration-assisted machining have been researched widely in the past, the selection of process parameters and the mechanism of surface integrity improvement under dry high-speed milling still need to be investigated in depth. In this research, we compare the surface topography, roughness, hardness, and residual stress of conventional milling (CM) and ultrasonic vibration side milling (UVSM) at four cutting speeds (40, 60, 80, and 100 m/min) and two feeds (0.01 and 0.02 mm/z) and reveal the mechanism of improving the surface integrity of Ti-6Al-4V under dry high-speed conditions. The results show that compared to CM, UVSM leads to a reduction in surface roughness, maintains a good surface profile at high feed, increases the residual compressive stress by up to 79%, and increases the surface hardness by 9.88%–14.06%. Its discontinuous cutting characteristics reduce cutting forces and heat accumulations, effectively improving surface integrity. However, higher cutting parameters lead to increased roughness and lower residual compressive stresses, requiring a balance between efficiency and quality. The research results provide process guidance for ultrasonic dry high-speed machining of Ti-6Al-4V, which is important for precision manufacturing.

Keywords: titanium alloy; ultrasonic vibration side milling; surface integrity; high-speed machining



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1. Introduction

Titanium alloys (e.g., Ti-6Al-4V) have been extensively utilized in the aerospace, shipbuilding, and medical industries, owing to their advantageous properties, including their low density, high specific strength, corrosion resistance, and compatibility [1,2]. Nevertheless, titanium alloy is widely regarded as a typical difficult material to machine

due to its high hardness and poor machinability. Titanium alloys are frequently susceptible to damage during cutting processes due to their high chemical reactivity, low thermal conductivity, and modulus of elasticity. Such damage may be attributed to a number of factors, including but not limited to excessive cutting forces, elevated cutting temperatures, severe tool wear, and substandard machining quality. Examples of cutting processes that may result in damage to titanium alloys include turning, milling, grinding, and drilling [3–6]. However, it is important to note that machining defects are unavoidable from both a macro and micro perspective and have the capacity to negatively affect surface integrity [7,8]. In the context of the burgeoning demand for high-end components in the field of aerospace manufacturing, coupled with the rapid advancements in manufacturing technologies, it is imperative to enhance the surface integrity of critical components. This enhancement is pivotal in optimizing their service performance, particularly with regard to fatigue performance, corrosion resistance, and wear resistance [9,10]. Many previous researches have shown that the good or bad surface integrity affects the serviceability of the components [11–14]. Consequently, enhancing the machinability of titanium alloys, as well as improving the surface integrity of machined titanium alloys, is imperative to optimize the service performance of key components.

During the machining of titanium alloys, the three factors of machining quality (surface integrity), machining efficiency, and sustainability (eco-friendliness) are often constrained by each other. It is difficult to synergize the three, so we often need to trade off the relationship between them. For example, while high-speed machining can significantly improve machining efficiency, previous research has shown that lower cutting speeds often result in better surface quality, but this in turn leads to reduced machining efficiency and increased production costs [15,16]. It has been demonstrated that the low thermal conductivity of titanium alloys results in the retention of heat at the interface between the tool and the chip during the cutting process. It has been demonstrated that this process can result in thermal deformation and a reduction in tool life. This, in turn, has the potential to result in an escalation in production costs [17]. The application of different cooling methods (e.g., minimal quantity lubrication (MQL) and high-pressure coolant) can make the heat of cutting titanium alloys dissipate quickly during the cutting process, which can significantly improve tool performance and tool life, as well as machining quality, but this can reduce the sustainability of cutting, cause a certain degree of pollution to the environment, and increase costs [18,19]. Therefore, how to synergistically improve the machining efficiency, machining quality, and sustainability of titanium alloys and trade off the relationship between the three has become a hot topic in academia and industry.

The surface integrity of materials is widely acknowledged to be influenced by the parameters of the machining process, including the tool material and geometry and the cooling methods employed (cutting fluid cooling, atomized cooling, gas protection cooling, etc.). In recent years, much research has been carried out in academia and industry to investigate how to improve the surface integrity of titanium alloys. It is obvious that better surface integrity can be achieved by using “gentle” machining methods (lower cutting speeds and feeds) and by selecting the proper tools and cooling methods. Furthermore, the implementation of energy field-assisted machining methodologies (e.g., ultrasonic machining, laser machining, electrochemical machining) has been demonstrated to enhance the surface integrity of titanium alloys. In the study conducted by Nath et al. [20], the impact of machining parameters on ultrasonic vibration cutting was examined. The investigation revealed that ultrasonic vibration frequency, amplitude, and cutting speed emerged as the primary factors influencing the process. The analysis indicated that an augmentation in ultrasonic vibration parameters, concomitant with a reduction in cutting speed, could enhance surface quality. In the study conducted by Rauf et al. [21], the cutting force

and tool wear in ultrasonic vibration-assisted milling of titanium alloys under different cooling methods were investigated. The research findings indicated that the depth of cut exerted the most significant influence on the cutting force. In addition, MQL was proved to be the optimal cooling strategy for machining of titanium alloys, with 33.49%, 16.93%, and 4.61% reduction in cutting forces compared to dry conditions, full liquid, and low-temperature cooling, respectively. He et al. [22] used laser-assisted machining of titanium alloys and found that laser-assisted machining improves the machinability of titanium alloys and reduces their subsurface damage. As demonstrated by Abu et al. [23], the electric discharge machining (EDM) of titanium alloys can be significantly enhanced by the selection of appropriate process parameters, thereby resulting in enhanced material removal rate and machining efficiency. In the study by Hu et al. [24], it was established that the longitudinal-bending hybrid ultrasonic vibration-assisted milling of titanium alloys significantly enhanced the cutting performance and surface quality of the alloys when compared to conventional milling (CM). The reduction in surface roughness was found to be 46.7%, while the cutting force was reduced by 43.2%. Gao et al. [25] investigated the machinability and surface quality of ultrasonic vibration milling of titanium alloy under dry conditions. The experimental results show that ultrasonic vibration milling can significantly improve the machinability and machining quality of titanium alloy. Compared with CM, the average cutting force can be reduced by up to 30.2%, the cutting temperature can be reduced by up to 25.9%, and the surface roughness can be reduced by up to 35.1%. Previous studies have shown that the selection of suitable machining methods, machining parameters, and cooling methods can significantly reduce cutting forces and cutting heat and improve machining quality and surface integrity.

High-speed machining, as an effective method for machining titanium alloys, can significantly improve machining efficiency and reduce machining costs. However, it is acknowledged that the high-speed cutting process gives rise to a concentration of cutting heat, a phenomenon that may exert a deleterious effect on machining quality. Kitagawa et al. [26] conducted a study on tool wear in high-speed cutting of titanium alloys. The researchers' findings demonstrated that as the cutting speed increased, the temperature in the cutting zone increased and the tool wear became more severe. It has been demonstrated that the adjustment of tool parameters and machining parameters has the effect of reducing the temperature of the cutting tool and extending the tool's life. Krishnaraj et al. [27] conducted a study on the high-speed end milling of titanium alloys. Their findings revealed that during such machining operations, severe heat concentration occurs on the cutting tool. This phenomenon has a detrimental effect on the quality of the machined surface and leads to significant tool wear. Wu et al. [28] employed finite element analysis to examine the chip formation process during high-speed cutting of titanium alloy. The findings of the present study demonstrate that the utilization of titanium alloy in high-speed cutting processes is conducive to the generation of serrated chips, a phenomenon that can be attributed to the insulation effect. It is evident that the augmentation of the rake angle of the tool has the capacity to diminish the degree of serrated chips to a certain extent. The extant research demonstrates that, whilst high-speed machining can enhance machining efficiency, it is susceptible to elevated cutting temperatures and significant tool wear, which consequently diminishes surface quality. Therefore, exploring the machining surface integrity under high-speed conditions and improving the surface quality have more practical significance for improving the service performance of titanium alloys.

Dry and quasi-dry machining technologies, as an effective way to achieve green manufacturing, have attracted much attention for eliminating the environmental pollution and resource consumption problems brought by traditional coolant. However, in the traditional dry cutting practice of Ti-6Al-4V titanium alloy, due to the low thermal conductivity and

high strength of the material, it is extremely susceptible to high cutting temperatures exceeding 1000 °C. This extreme thermal coupling not only significantly intensifies diffusive and oxidative wear of the tool but also leads to the generation of micro-cracks in the machined surface layer, phase-change layer, and other micro-defects, which seriously affects the fatigue performance and service life of the component [17]. Jamil et al. [29] investigated the correlation between machining quality, efficiency, and sustainability in the cutting of titanium alloys. Their findings indicated that the implementation of suitable cooling methodologies can enhance the machining quality of titanium alloys and prolong the tool life. However, it was also observed that this approach can result in a certain degree of pollution and waste generation. In comparison with dry cutting, the utilization of CO₂ snow, LN₂, and MQL enhanced surface quality by 53.8%, 39.7%, and 32.8%, respectively, while concomitantly reducing tool wear by 54%, 42%, and 24%, respectively. This underscores the intricacy inherent in the selection of environmentally friendly cooling methodologies. The present study will compare two green manufacturing processes, namely dry and MQL, with a view to identifying the most sustainable option. Liu et al. [30] found that MQL with some cooling and lubrication significantly extended tool life compared to dry conditions. In addition, different combinations of coated tools and cooling strategies can also have a certain impact on tool life, and when using tools with different coatings, they should also correspond to different cooling methods.

Ultrasonic vibration-assisted cutting is a method of cutting materials that has been shown to reduce cutting forces, cutting temperatures, and surface roughness. It is anticipated that this will yield manufacturing processes that are characterized by high quality, high efficiency, and sustainability. As an advanced machining method, ultrasonic vibration-assisted machining has been widely used in machining various advanced materials (high-temperature alloys, titanium alloys, high-strength steels, composites, etc.) as well as in various types of cutting operations (turning, milling, grinding, drilling, etc.) [31–33]. It is evident that ultrasonic vibration side milling (UVSM) possesses numerous advantages, including the reduction of cutting forces, enhanced machining efficiency and quality, minimized burr presence, and improved process stability [34]. Yin et al. [35] conducted an exploration of the tool wear problem in high-speed ultrasonic shot peening milling of high-temperature alloys. A comparison was made of the tool life of high-speed ultrasonic shot peening milling with that of conventional milling. The findings revealed that the former could be extended by a maximum of 32.5%, and the latter could be increased by a maximum of 17 times. Wang et al. [36] investigated the tool wear problem of longitudinal ultrasonic vibratory milling of high-temperature alloys. The test results showed that longitudinal ultrasonic vibration milling has the advantages of reducing cutting force and improving tool life, which increased by 33% compared with the traditional milling tool life. Chen et al. [37] established that the implementation of ultrasonic vibration resulted in a reduction of surface roughness, an augmentation of surface deformation layer thickness, and an escalation of residual compressive stresses through ultrasonic vibration spiral milling of titanium alloys. Qin et al. [38] investigated the effect of spindle speed and feed per tooth on the surface hardness of longitudinal torsion ultrasonically assisted milling of titanium alloys. The investigation revealed that the surface hardness of the titanium alloy diminished with an augmentation in the feed per tooth and the spindle speed. The highest recorded hardness of 438.61 HV was obtained at a spindle speed of 1000 r/min and a feed per tooth of 0.01 mm/z. Liu et al. [39] found that rotational ultrasonic elliptical milling significantly improved the cutting performance and surface integrity during milling of high-temperature alloys using a ball end mill. The UVSM provides a new approach to trade off machining quality, machining efficiency, and sustainability of titanium alloys under dry conditions and high-speed cutting conditions.

It is acknowledged that a significant corpus of research has been dedicated to the enhancement of machining quality, efficiency, and sustainability in the context of titanium alloys. However, the majority of research in this field has focused on improving machinability (reduction in cutting forces, cutting heat, and cutting stability) [40–42]. However, further research is required into the potential for enhancing the surface integrity of titanium alloys, particularly in the context of high cutting speeds and drying conditions, through the utilization of UVSM. The objective of this research is to examine the impact of UVSM on the surface integrity of Ti-6Al-4V under conditions of high speed and drying.

The main research content of this study is as follows: Firstly, CM and UVSM at different cutting speeds (40–100 m/min) and feed rates per tooth (0.01 and 0.02 mm/z) were conducted as comparative experiments. Secondly, the machined workpieces were subjected to a series of surface integrity characterizations (surface roughness, surface topography, micro-hardness, and residual stress). Finally, the effectiveness of UVSM in improving the surface integrity of Ti-6Al-4V at high cutting speeds as well as under dry conditions was demonstrated by comparing the surface integrity of the workpieces obtained by UVSM and CM. In conclusion, the results of this research can provide an important reference value for the high-quality, high-efficiency, and green machining of titanium alloys at high speed and dry conditions.

2. Materials and Methods

2.1. Materials and Workpieces

The workpiece material used in this study was Ti-6Al-4V titanium alloy, a cubic forging block with a size of $30 \times 30 \times 30$ mm ($L \times W \times H$). Ti-6Al-4V is an $\alpha + \beta$ phase alloy, and the microstructure of α phases and β phases under SEM is shown in Figure 1. According to the data provided by the manufacturer, the chemical composition and mechanical properties of Ti-6Al-4V are shown in Tables 1 and 2, respectively. To ensure the reliability of the surface integrity results, the samples are processed from the same manufacturer and production batch to reduce errors caused by metallurgical differences.

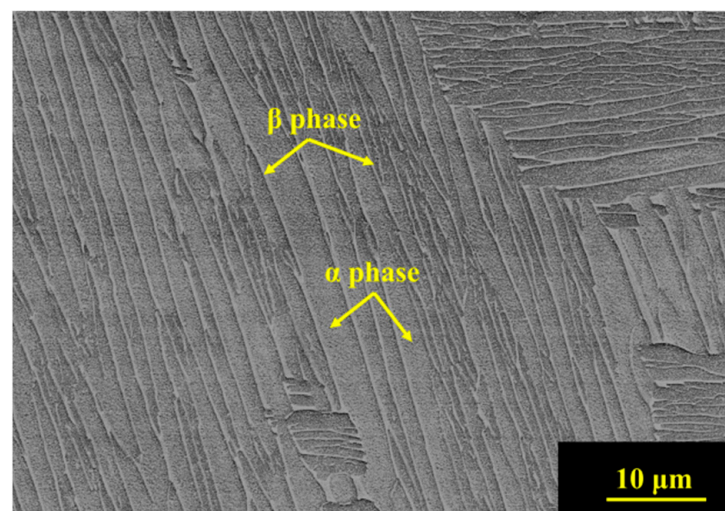


Figure 1. Typical microstructure of Ti-6Al-4V titanium alloy.

Table 1. Chemical composition of Ti-6Al-4V titanium alloy (wt.%) [43].

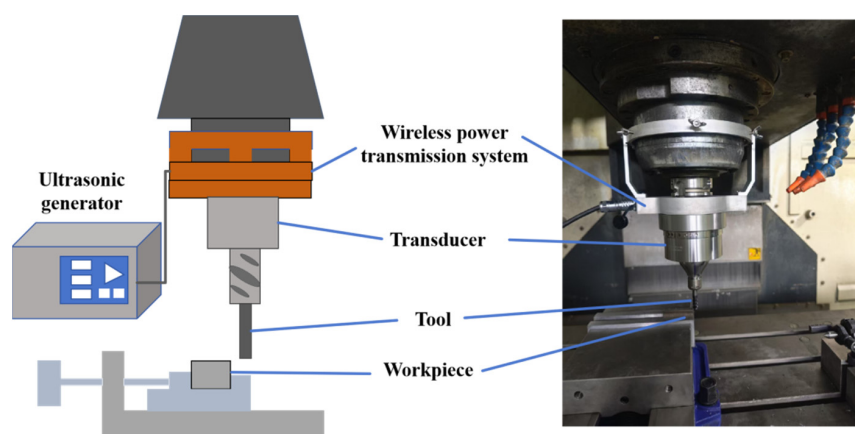
Ti	Al	V	Fe	O	C	N	H
88.1–91	5.5–6.75	3.5–4.5	≤0.25	≤0.2	≤0.08	≤0.05	≤0.01

Table 2. Mechanical properties of Ti-6Al-4V titanium alloy [44].

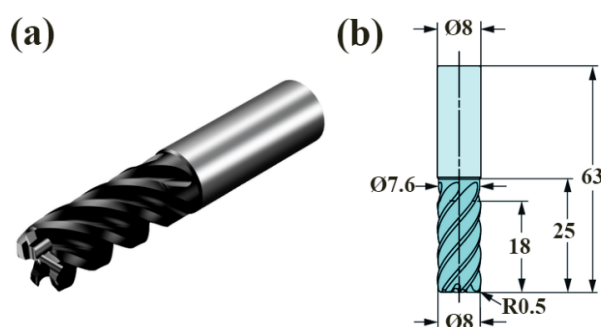
Density (kg/m ³)	Hardness (HV)	Elastic Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)
4429	300	114	835	905

2.2. Experimental Setup

The high-speed milling experiments were conducted on a VMP-45A vertical machining center with a maximum spindle speed of 15,000 r/min. The ultrasonic vibratory milling experimental setup included an ultrasonic generator, a transducer, a workpiece, and a milling tool, as shown in Figure 2. The ultrasonic generator and transducer used in the experiment were produced by TSINGDING (Shenzhen, China). CM and UVSM were operated by switching the ultrasonic power supply on or off. The PVD-coated carbide tool (2F340-0800-050-SC1745) manufactured by SANDVIK (Stockholm, Sweden) was used for experiments. The specific tool parameters are shown in Table 3, and the milling tools are shown in Figure 3.

**Figure 2.** Dry high-speed ultrasonic vibration side milling Ti-6Al-4V alloy experimental device.**Table 3.** Tool parameters for CM and UVSM titanium alloy experiments.

Parameter (Unit)	Value
Material	Carbide
Coating	PVD TiAlSiN
Spiral length (mm)	25
Cutting edges	5
Diameter (mm)	8
Helix angle (°)	42
Rake angle (°)	5

**Figure 3.** Physical diagrams and schematic drawings of milling tools: (a) Milling tool physical diagram and (b) milling tool schematic diagram (unit: mm).

To determine the effect of CM and UVSM on the surface integrity of Ti-6Al-4V titanium alloys at different parameters, feed rate per tooth (f_z) and cutting speed (v) were chosen as variables for the research. The experimental conditions of UVSM are presented in Table 4.

Table 4. Machining parameters of titanium alloy Ti-6Al-4V in CM and UVSM.

Parameters (Unit)		Value	
Milling conditions	Axial cutting depth a_p (mm)	1	
	Radial cutting depth a_e (mm)	2	
	Feed rate per tooth f_z (mm/z)	0.01, 0.02	
	Cutting speed v (m/min)	40, 60, 80, 100	
Vibration conditions	Milling process methods	CM	HVSM
	Frequency (Hz)	/	19586
	Amplitude (μm)	/	8 (peak to peak)

2.3. Surface Integrity Characterization

To verify the effectiveness of UVSM in improving the surface integrity of Ti-6Al-4V, surface integrity measurements (surface topography, surface roughness, micro-hardness, and residual stresses) were conducted on CM and UVSM workpiece surfaces.

(1) Surface topography and surface roughness

For accurate detection of surface topography and surface roughness after milling, a Bruker NPFLEX (Billerica, MA, USA) surface profile measurement system was used in this study. Vision64 software was used to analyze the obtained interference fringes and finally obtain the surface roughness values. The parameters of surface roughness measurement are as follows: the eyepiece is $1.0\times$, the objective lens is $10\times$, and the sampling area is set to $0.8\text{ mm} \times 0.8\text{ mm}$. To ensure the accuracy of the measurements, each sample should be measured four times, and the average value is taken as the surface roughness result after eliminating the abnormal values.

(2) Micro-hardness

In this study, the micro-hardness of CM and UVSM workpiece surfaces was measured using an HVW-1000Z (Jinan, China), automated micro-hardness testing device. The loading load was 0.25 N, and the dwell time was 10 s. To ensure the accuracy of the measurements, three different locations were chosen for the measurement points of each specimen, and the average value was finally chosen as the result.

(3) Residual stress

Surface residual stresses on CM and UVSM workpieces were analyzed using a PROTO L-XRD (Vancouver, BC, Canada) residual stress analyzer. The analyzer tube voltage, tube current, target material, spot diameter, and diffraction angle were 30 kV, 25 mA, Cr target, 1 mm, and 156.1° , respectively. To ensure the accuracy of the measurements, three different positions of the measurement points should be selected for each sample, and the average value was finally chosen as the result.

3. Results and Discussion

3.1. Surface Topography

Figures 4 and 5 show the Ti-6Al-4V alloy surface topography of CM and UVSM at $f_z = 0.01$ and 0.02 mm/z , respectively. We can see from Figures 4 and 5 that the CM machined surface showed vertical stripes, which was due to the continuous cutting characteristic of CM machining, where adjacent cutting edges formed a ridge-like topography on the machined surface, leading to the appearance of the vertical texture shape. The texture

distance was related to f_z , and both the distance and height of the texture increased when the f_z increased, while the cutting speed had less effect on the texture density. The UVSM machined surface showed densely distributed vibratory cutting textures with significant peak-to-valley differences. At lower cutting speeds of 40 and 60 m/min, the UVSM surface increased a lot of vibratory cutting textures, while at higher cutting speeds of 80 and 100 m/min, the surface topography was densely distributed with vibratory cutting textures, while the feed textures of CM were not significant. This indicates that the surface texture of CM was mainly affected by f_z , while the surface topography of UVSM was affected by both cutting parameters and ultrasonic vibration parameters. UVSM can also significantly improve the machined surface topography at high cutting speeds and reduce the feed textures, thus enhancing the surface quality. By comparing the surface topography, it is found that the CM-machined surface exhibits obvious parallel linear grooves, and the bottom of the grooves is susceptible to stress concentration, which is unfavorable to its service performance. The high-frequency separation between the tool and the workpiece during the UVSM process reduces tool wear and improves the surface topography of the machined area. In addition, the high-frequency ironing effect of UVSM also favors the improvement of the surface quality of Ti-6Al-4V alloy. However, with the increase of cutting speed, the UVSM and CM machining surface quality is poor, and the surface adhesion and pitting phenomenon proliferate, and all these factors will reduce the service performance of the material and shorten its service life.

3.2. Surface Roughness

Surface roughness is a significant indicator of surface integrity, playing a pivotal role in the fatigue and wear resistance of components. As demonstrated in Figures 6 and 7, the impact of UVSM and CM on surface roughness was investigated at various cutting speeds, with f_z set at 0.01 and 0.02 mm/z. The surface roughness of CM showed a decreasing and then increasing trend with the increase in cutting speed, while UVSM showed an overall increasing trend. This is mainly because when the cutting speed was low, the temperature in the cutting area was too high and the surface finish quality was poor, which was not favorable to its surface roughness. It is evident that an augmentation in the cutting speed invariably gives rise to an escalation in surface roughness. This phenomenon can be attributed to the concomitant rise in both cutting forces and cutting heat, in addition to an increase in friction between the tool and the workpiece. Consequently, this results in an increase in surface roughness. In the context of the present study, it was observed that when the value of f_z was set at 0.01 mm/z, the surface roughness of CM exhibited fluctuations between 0.8 μm and 0.9 μm , in accordance with the escalating cutting speeds. Concurrently, the surface roughness of UVSM demonstrated an augmentation from 0.586 μm to 0.704 μm . The surface roughness of CM reached a minimum of 0.594 μm when $f_z = 0.02$ mm/z and $v = 80$ m/min, and the surface roughness of UVSM reached a minimum of 0.521 μm when $f_z = 0.02$ mm/z and $v = 60$ m/min, which is 28.83% lower than that of 0.732 μm for CM.

Furthermore, it can be seen from Figures 6 and 7 that the surface roughness of UVSM is lower than that of CM for the same cutting parameters. For example, the surface roughness of the UVSM was 0.586 μm when $f_z = 0.01$ mm/z and $v = 40$ m/min, which was much lower than that of the CM of 0.894 μm . This was mainly due to the intermittent cutting mechanism of the UVSM, which resulted in lower cutting forces and heat. On the one hand, the lower cutting force reduces the damage of the cutting edge on the workpiece surface, which is beneficial to improving the surface quality. On the other hand, the continuous chips are converted into intermittent small chips, which reduces the entanglement of chips and improves the surface quality. In addition, the high-frequency reciprocating vibration of

the UVSM has a certain ironing effect on the surface, resulting in greater plastic deformation of the machined surface, which makes the machined surface smoother.

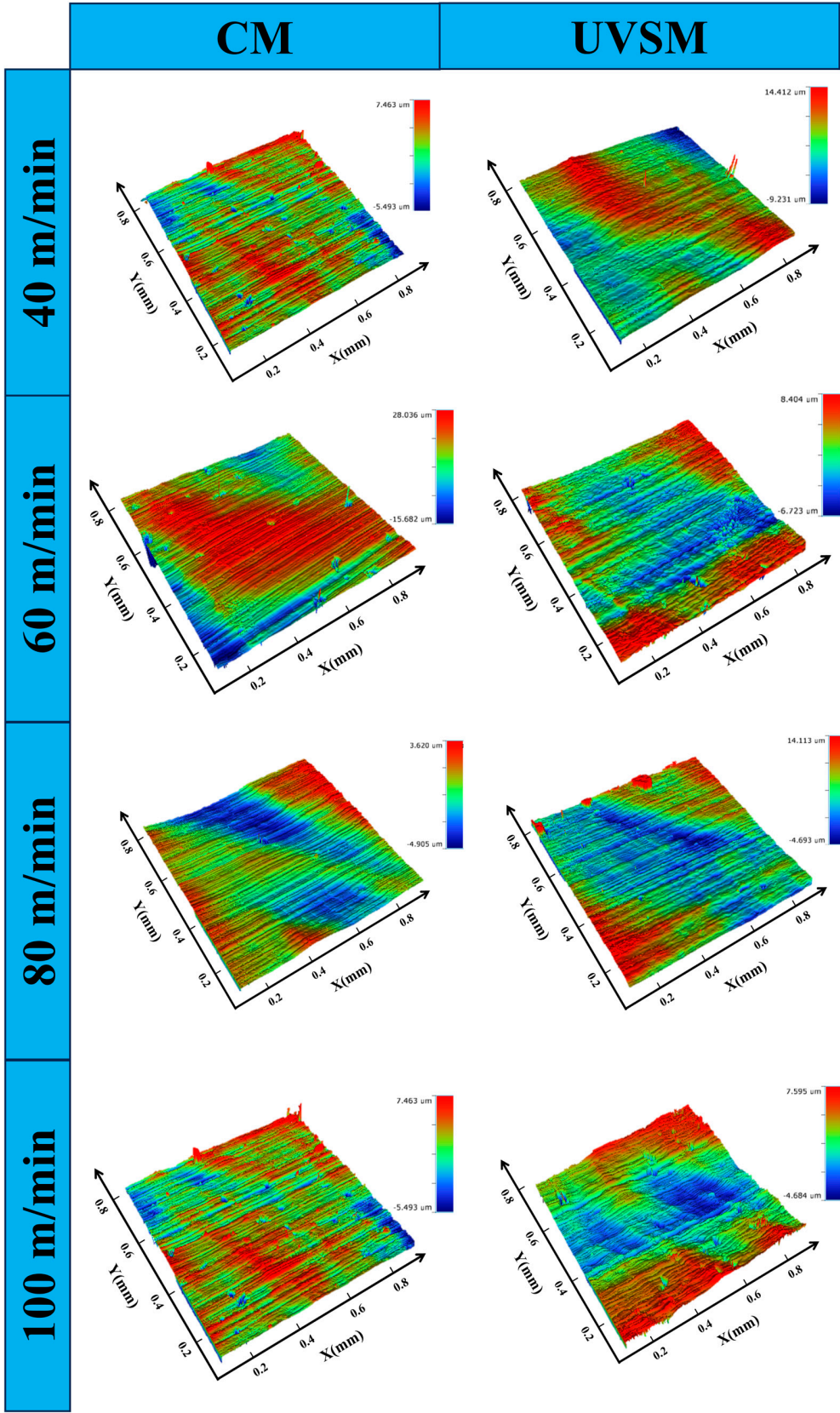


Figure 4. Effect of different cutting speeds on surface topography obtained under CM and UVSM at $f_z = 0.01$ mm/z.

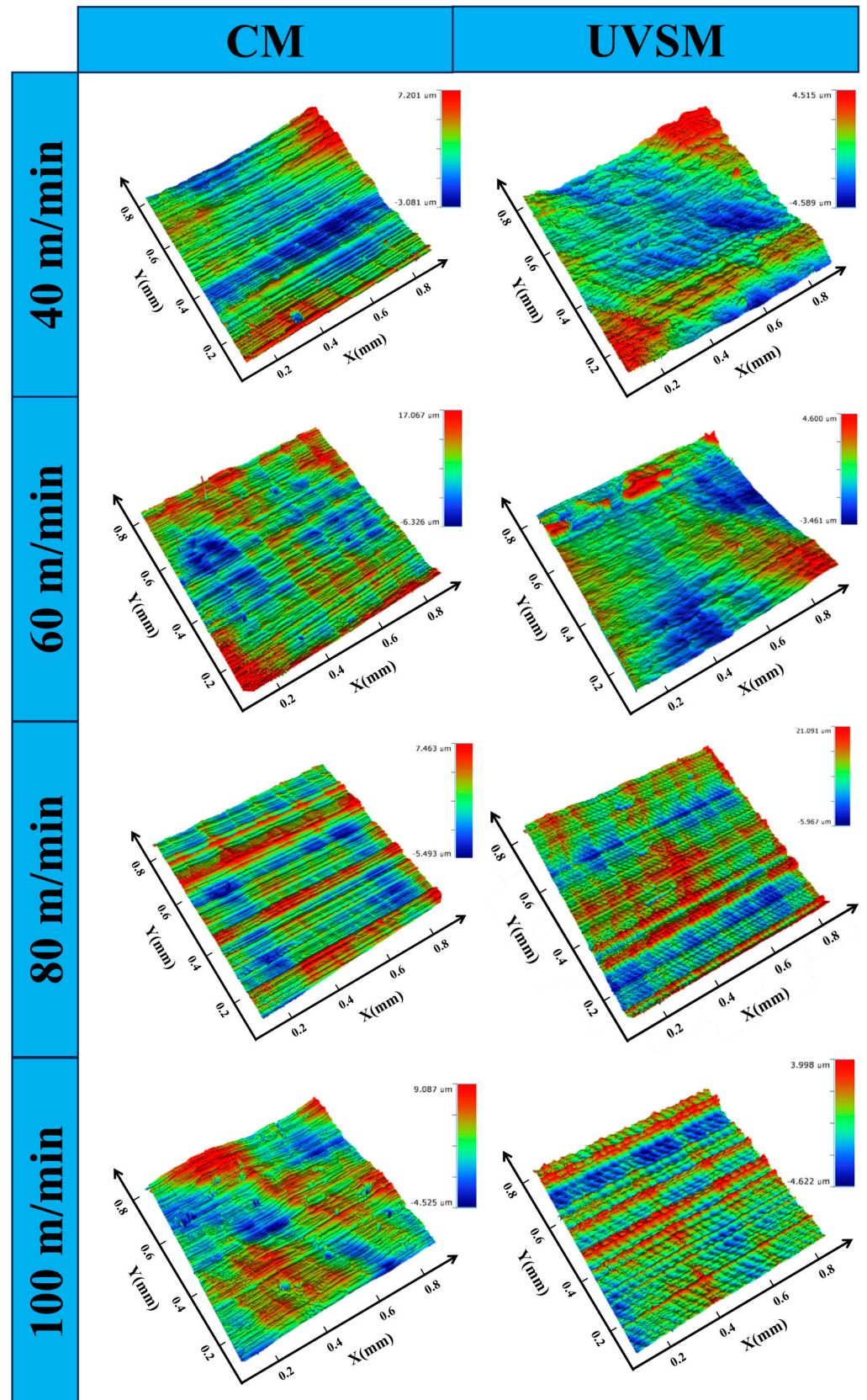


Figure 5. Effect of different cutting speeds on surface topography obtained under CM and UVSM at $f_z = 0.02$ mm/z.

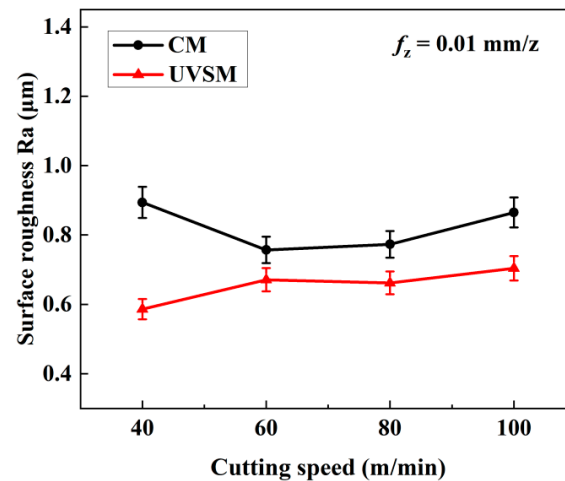


Figure 6. Effect of different cutting speeds on surface roughness obtained under CM and UVSM at $f_z = 0.01$ mm/z.

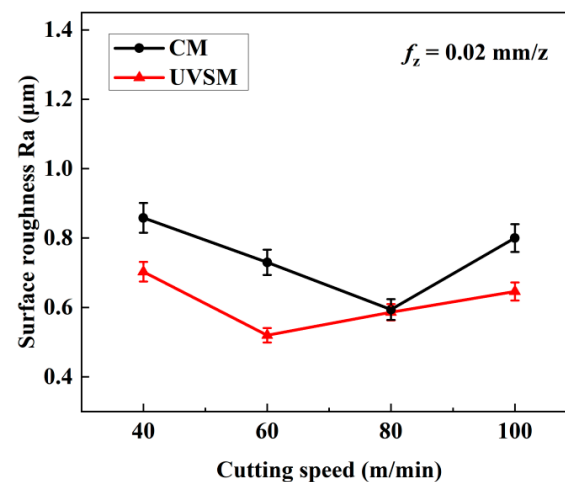


Figure 7. Effect of different cutting speeds on surface roughness obtained under CM and UVSM at $f_z = 0.02$ mm/z.

3.3. Surface Micro-Hardness

Work hardening is a prevalent phenomenon in the processing of plastic metallic materials, where the surface of the workpiece is impacted by shear slip and plastic deformation during machining, as well as by ironing friction on the flank face of the tool on the machined surface. This results in the surface hardness of the workpiece being higher than the hardness of the workpiece substrate [45]. As demonstrated in earlier studies, work hardening enhanced the strength and hardness of the material, thereby augmenting the wear resistance of the workpiece. Furthermore, the enhanced surface micro-hardness led to a reduction in workpiece deformation caused by alternating load, a deceleration of fatigue crack expansion, and an improvement in fatigue performance. A multitude of factors have been identified as affecting the surface micro-hardness of the workpiece. The primary factor responsible for this effect is the coupling effect of cutting force and cutting heat. On the one hand, the role of cutting force intensifies the plastic deformation of the workpiece material; on the other hand, during the machining process, the cutting heat can soften the workpiece material to a certain extent, thus reducing the micro-hardness of the workpiece material.

Figures 8 and 9 show the effect of UVSM and CM on the surface micro-hardness at different cutting speeds when $f_z = 0.01$ and 0.02 mm/z. It can be seen from the results that

the workpiece micro-hardness of both UVSM and CM increased with the increasing of cutting speed. At $f_z = 0.01$ mm/z, the surface micro-hardness of CM and UVSM increased from 301.96 HV to 337.93 HV and from 319.31 HV to 366.45 HV with the increase in cutting speed from 40 to 100 m/min, with an increase of 11.91% and 14.76%, respectively.

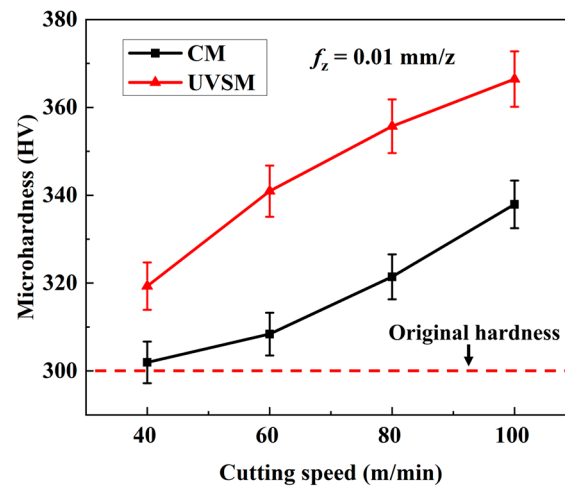


Figure 8. Effect of different cutting speeds on micro-hardness obtained under CM and UVSM at $f_z = 0.01$ mm/z.

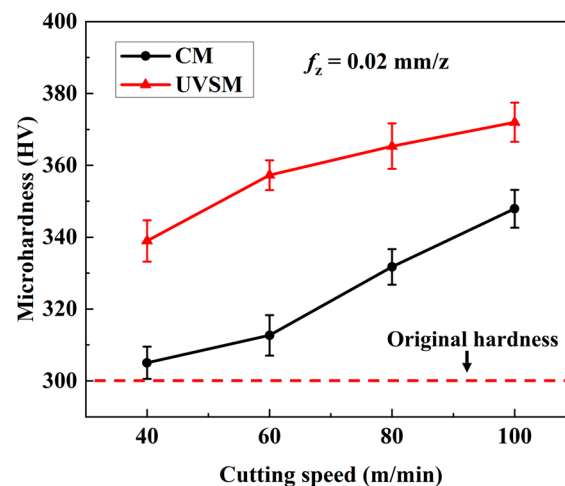


Figure 9. Effect of different cutting speeds on micro-hardness obtained under CM and UVSM at $f_z = 0.02$ mm/z.

In addition, UVSM obtained higher surface micro-hardness than CM under the same cutting parameters. This may be because the intermittent cutting effect of UVSM caused periodic contact and separation between the tool and the workpiece, which effectively reduced the temperature in the cutting area. In addition, the intermittent cutting mechanism of the UVSM results in reduced contact time between the tool and the workpiece per unit of time when compared with the CM. Consequently, it can be deduced that the workpiece will be less affected by heat with UVSM and that the surface of the workpiece will be softened to a lesser extent than with CM. This process has been shown to enhance the hardening of the machined surface. The maximum surface micro-hardness obtained by UVSM was 372.45 HV, which increased by 7.05% compared to 347.93 HV of CM when the $f_z = 0.02$ mm/z and $v = 100$ m/min.

3.4. Surface Residual Stress

It is widely acknowledged that fatigue failure is typically precipitated by the emergence of surface cracks, a consequence of residual tensile stresses. Conversely, residual compressive stresses have been shown to impede crack propagation, thereby enhancing the durability of the workpiece [46].

Figures 10 and 11 show the effect of UVSM and CM on the surface residual stresses at different cutting speeds for $f_z = 0.01$ and 0.02 mm/z, respectively. As we can see from the figure, the surface residual stresses of both CM and UVSM were compressive stresses, and with the increase in cutting speed, the surface residual compressive stresses of both showed a decreasing trend. At $f_z = 0.01$ mm/z and $v = 60$ mm/min, the residual compressive stress of CM was -277.79 MPa, and the residual compressive stress of UVSM was -377.87 MPa, which increased by 36%. At $f_z = 0.02$ mm/z and $v = 40$ mm/min, the residual compressive stress of CM was -217.69 MPa, and the residual compressive stress of UVSM was -389.31 MPa, which increased by 79%. This phenomenon can be attributed to the primary influence of residual stresses on the interaction of thermal and mechanical stresses during the machining process. Residual stress resulting from mechanical stress is typically compressive, whereas residual stress arising from thermal stress is generally tensile in nature. As the cutting speed increases, the temperature of the cutting area rises, and the influence of thermal stress gradually becomes dominant. Concurrently, the surface layer undergoes plastic deformation, resulting in a reduction in mechanical stress and, consequently, surface compressive stress.

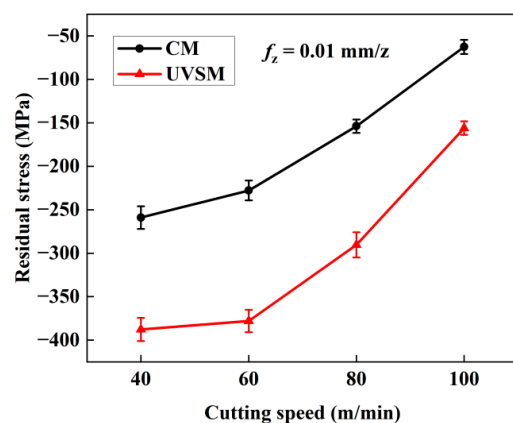


Figure 10. Effect of different cutting speeds on residual stresses obtained using CM and UVSM at $f_z = 0.01$ mm/z.

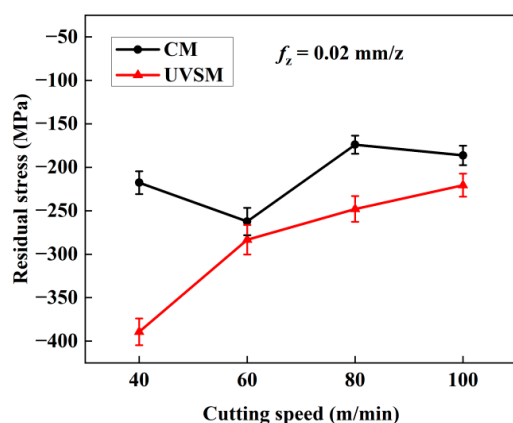


Figure 11. Effect of different cutting speeds on residual stresses obtained under CM and UVSM at $f_z = 0.02$ mm/z.

In addition, under identical cutting parameters, UVSM exhibited a higher surface residual compressive stress in comparison with CM. UVSM employs an intermittent cutting mechanism, which has been demonstrated to effectively mitigate cutting heat and minimize the impact of thermal effects on surface residual stress. Concurrently, the high-frequency ironing effect of UVSM is conducive to the formation of residual compressive stress on the surface of the workpiece material. In summary, UVSM has the capacity to obtain higher residual compressive stress under a range of cutting conditions, thereby exerting a favorable influence on the in-service performance of the Ti-6Al-4V alloy.

4. Conclusions

The present study investigated the surface integrity of Ti-6Al-4V alloys machined using UVSM, including surface morphology, roughness, micro-hardness, and residual stress distribution, under dry and high-speed milling conditions. The primary conclusions of the study are as follows:

- (1) Under the same cutting speed, due to intermittent cutting and high-frequency ironing, UVSM has better machining quality under dry conditions. With the increase of cutting speed, machining defects of CM and UVSM increase, and the surface quality decreases gradually, which is unfavorable for its service performance.
- (2) By comparing the variation in surface roughness during the cutting processes of CM and UVSM, it was found that surface roughness generally increases with cutting speed for the Ti-6Al-4V alloy. However, UVSM was found to significantly improve surface roughness. At $v = 60$ m/min and $f_z = 0.02$ mm/z, the lowest surface roughness achieved by UVSM was $0.521\text{ }\mu\text{m}$, 28.83% lower than the $0.732\text{ }\mu\text{m}$ achieved by CM.
- (3) Increases in cutting speed result in rises in the micro-hardness of both CM and UVSM under high-speed dry milling conditions. At $f_z = 0.01$ mm/z, the surface micro-hardness of CM and UVSM increases from 301.96 HV to 337.93 HV (up to 11.91%) and from 319.31 HV to 366.45 HV (up to 14.76%), respectively. At $f_z = 0.02$ mm/z, the surface micro-hardness of CM and UVSM increased from 305.04 HV to 347.93 HV (up to 14.06%) and from 338.95 HV to 372.45 HV (up to 9.88%), respectively. When $f_z = 0.02$ mm/z and $v = 100$ m/min, UVSM obtained the maximum surface micro-hardness of 372.45 HV.
- (4) The surface residual stresses produced by CM and UVSM were mainly residual compressive stresses. In addition, under high-speed dry milling conditions, the surface residual compressive stresses on both CM and UVSM decrease as the cutting speed increases. At $f_z = 0.02$ mm/z, the surface residual compressive stress of UVSM decreases from -389.31 MPa to -220.55 MPa. Because of the intermittent cutting and ironing effect of UVSM, its surface residual compressive stress is much larger than that of CM. At $f_z = 0.02$ mm/z and $v = 40$ mm/min, the maximum surface residual stress of UVSM is -389.31 MPa, which is 79% higher than that of CM.

In conclusion, the intermittent cutting and ironing effect of UVSM results in a superior surface quality, diminished surface roughness, and augmented surface micro-hardness and residual stresses in Ti-6Al-4V titanium alloy. Consequently, as an efficient precision machining method, UVSM can significantly improve the surface integrity of Ti-6Al-4V titanium alloys under high-speed cutting and dry milling conditions. This has been demonstrated to enhance surface integrity, increase productivity, and reduce production costs. However, the extant research only discusses and analyzes surface integrity; the analysis of fatigue performance and wear resistance is absent. Consequently, subsequent studies will explore how UVSM affects the fatigue and wear resistance of titanium alloy parts.

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