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Experimental Study on Cutting Force and Surface Integrity of TC4 Titanium Alloy with Longitudinal Ultrasonic-Assisted Milling

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Abstract: The ultrasonic vibration-assisted milling process was used to study the difficult-to-machine aerospace material titanium alloy TC4 and explore the milling parameters that fit the processing. Based on the orthogonal experimental method, the changes in cutting force, roughness, and surface morphology under conventional and ultrasonic-assisted milling conditions were studied, and the relationship between various processing parameters and their effects was obtained. The results showed that the cutting force was most affected by the feed per tooth and cutting depth. Adding ultrasonic vibration could change the surface texture and significantly impact roughness. By adding an appropriate amplitude of ultrasonic-assisted milling, the maximum average cutting force can be reduced by more than 20.66%, and the maximum surface roughness can be reduced by 44.23%, making the workpiece surface produce regular “sine/cosine” patterns and improving the surface quality of the workpiece. Compared with conventional milling, the deformation layer of the workpiece slightly increased under ultrasonic-assisted milling. The cutting force and surface roughness of titanium alloy TC4 under ultrasonic-assisted milling were reduced. A reasonable selection of processing parameters can further improve cutting force and other parameters, providing a reference basis for the processing of aerospace materials.

Keywords: longitudinal ultrasonic-assisted milling (LUAM); titanium alloy TC4; cutting force; surface roughness; surface morphology



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1. Introduction

Titanium alloys have excellent comprehensive properties, such as low density, high strength, high temperature resistance, and corrosion resistance, and their application in fields such as aviation, aerospace, navigation, and automobiles has received special attention. Titanium alloys have the characteristics of a low deformation coefficient, high temperature strength, and low elastic modulus; it is worth mentioning that the specific strength of the best titanium alloy is almost twice that of alloy steel, so during the cutting process the tool wear is severe, the cutting force is large, the cutting temperature is high, and the processing quality is uncontrollable. The relative cutting performance is poor. With the widespread use of titanium alloys, conventional cutting processes inevitably limit titanium alloy components' precision, efficiency, and high-quality processing. Compared to conventional machining, ultrasonic-assisted machining with high frequency and small amplitude has exhibited good cutting performances for advanced materials. In recent years, advances in the ultrasonic generator, ultrasonic transducer, and horn structures have led to the rapid progress in the development of ultrasonic-assisted machining [1]. The application of an ultrasonic vibration system has evolved from one-dimensional to three-dimensional. The cutting characteristics and mechanism of periodic contact separation between tool and workpiece have also been deeply studied, and a variety of theoretical models have also

been repeatedly verified and improved in a large number of practices [2,3]. Ultrasonic-assisted machining technology can effectively reduce cutting force [4,5], improve part of the surface characteristics [6], and refine subsurface microstructure, due to its pulse enhancement effect [7], cavitation effect, and other characteristics of intermittent cutting. It is an important development direction to apply ultrasonic-assisted machining technology to the cutting process of difficult-to-machine materials [8,9]. In addition, compared with conventional cutting processes, during the ultrasonic-assisted machining process, due to the dynamic stress state, high strain rate, and local thermal-mechanical coupling, the subsurface structure of the workpiece inevitably changes [10]. However, there is currently little research on the phase transformation of the surface and subsurface during ultrasonic-assisted machining, so it is important to study the microstructure evolution mechanism of the surface and subsurface of titanium alloys during ultrasonic-assisted machining [11]. Currently, research on titanium alloy materials mainly focuses on high-speed cutting [12,13], machining deformation [14], material modification [15], composite machining [16], and other machining methods. The main evaluation indicators for related research are cutting force [17,18], cutting heat [19,20], chip morphology [21,22], tool wear [23–27], and surface microstructure [28], and the main research objectives are to improve machining efficiency and surface quality.

The fatigue failure of parts originates from surface or subsurface defects, and all wear and corrosion of parts occurs on the surface [29,30]. The quality of the processed surface and the microstructure state of the subsurface area have a significant impact on preventing component failure and extending service life [31,32]. Therefore, the integrity of the machined surface of key components has become an important evaluation indicator of manufacturing quality. At present, there are many studies evaluating the surface and subsurface properties of cutting processing, which not only depend on the characteristics of the material itself, but also on the processing method used [33,34]. Tej Pratap et al. used the Johnson–Cook constitutive equation to establish a cutting force model during the milling process. Through simulation, the stress distribution, cutting force stress distribution, and mechanism of titanium alloy Ti6Al4V during the milling process were studied. Combined with experimental content, the cutting force was successfully simulated and the correctness of the model was verified [35]. Niu Ying et al. conducted longitudinal and torsional ultrasonic vibration-assisted milling on titanium alloy Ti6Al4V. They compared the differences in cutting force, residual stress, and cutting temperature under traditional milling, and combined orthogonal experiments and single-factor experiments to study the influence of residual stress and other parameters. Finally, it was concluded that longitudinal and torsional ultrasonic vibration-assisted milling can effectively reduce cutting force and cutting temperature and increase surface residual compressive stress [36]. Wang Xiaoming et al. studied the surface roughness of titanium alloy TC4 under high-speed milling, and used orthogonal experiments to analyze the influence of various milling parameters on surface roughness. By analyzing the range, the trend of the influence of milling parameters on surface roughness was described [37].

This article focuses on the study of TC4 titanium alloy. Under the condition of longitudinal ultrasonic-assisted milling, an orthogonal experimental design is proposed to investigate the effects of milling parameters on cutting force, roughness and surface morphology, and the section layer changes of the workpiece under ultrasonic-assisted machining conditions. The results provide a basis for precision and ultra-precision machining of TC4 titanium alloy.

2. Materials and Methods

2.1. Longitudinal Ultrasonic Milling Characteristics

A Cartesian coordinate system was established in this study based on the milling process system, and ultrasonic-assisted milling was adopted. The tool had a high-frequency periodic displacement in the axial direction. During processing, the tool's vibration was applied to the milling workpiece, thereby changing the cutting force and surface roughness

during milling. The tool edge motion path in the LUAM system can be expressed by the following system of equations:

$$\begin{cases} x(t) = R \sin \frac{2\pi n_s t}{60} \\ y(t) = v_w t + R \cos \frac{2\pi n_s t}{60} \\ z(t) = A \sin(2\pi f_z t) \end{cases} \quad (1)$$

where R is the tool radius, n_s is the tool rotation speed around the main axis, v_w is the tool cutting speed along the y -axis, A is the longitudinal amplitude of the ultrasonic wave, and f_z is the longitudinal vibration frequency of the ultrasonic wave, while $z(t) = 0$ represents no ultrasonic assistance, i.e., conventional milling (CM).

The LUAM principle and tool edge motion path model are illustrated in Figure 1.

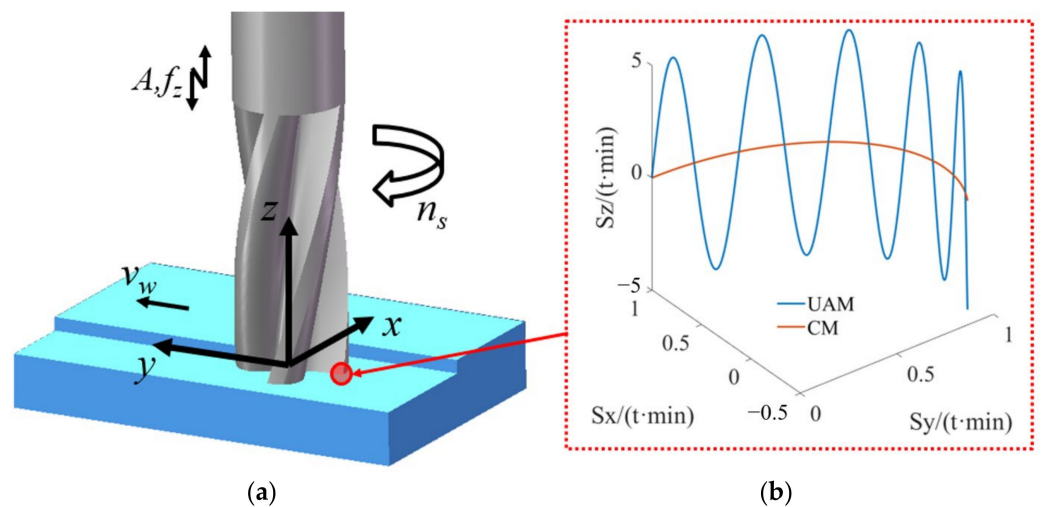


Figure 1. LUAM principle. (a) Milling model; (b) Tool edge motion path.

2.2. Experimental Setup

The milling test machine used in this study comprised a CNC machining center (Henfux-HFM 700 L) coupled with an ultrasonic processing system and a cutting force measurement acquisition system (Swiss Kistler Instruments Co., Ltd., Winterthur, Switzerland), milling force-acquisition system type 9119AA2, and with a signal amplifier (type 5080A) on the machine. The machine spindle included a piezoelectric transducer, an ultrasonic amplitude rod, and a tool holder. The experimental setup is shown in Figure 2.

During operation, the transmitting coil fixed on the machine spindle and the receiving coil rotating coaxially with the spindle generated induction to power the transducer. The piezoelectric transducer generated the ultrasonic vibration in the coaxial direction along the spindle axis, with a vibration frequency of 24.8 kHz. The appropriate processing amplitude was amplified by the amplitude rod and transferred to the tool cutting edge.

The TC4 titanium alloy cutting test piece (workpiece) had $15 \text{ mm} \times 6 \text{ mm} \times 8 \text{ mm}$ dimensions. The TC4 grade alloy was an $\alpha + \beta$ dual-phase Ti-6Al-4V alloy, containing 5.5% α -phase Al and 3.5% β -phase V stabilizing elements. Al improved the alloy's room-temperature and high-temperature strengths by solid-solution strengthening of the α -phase in the Ti-Al-V system. V was one of the few alloying elements in titanium alloys that could improve both strength and plasticity. The material composition [38] (mass fraction, %) was as follows: Al (5.5%–6.8%), V (3.5%–4.5%), Fe (0.30%), C (0.10%), N (0.05%), O (0.20%), H (0.015%), and Ti (balance). Its mechanical properties [39] are shown in Table 1.

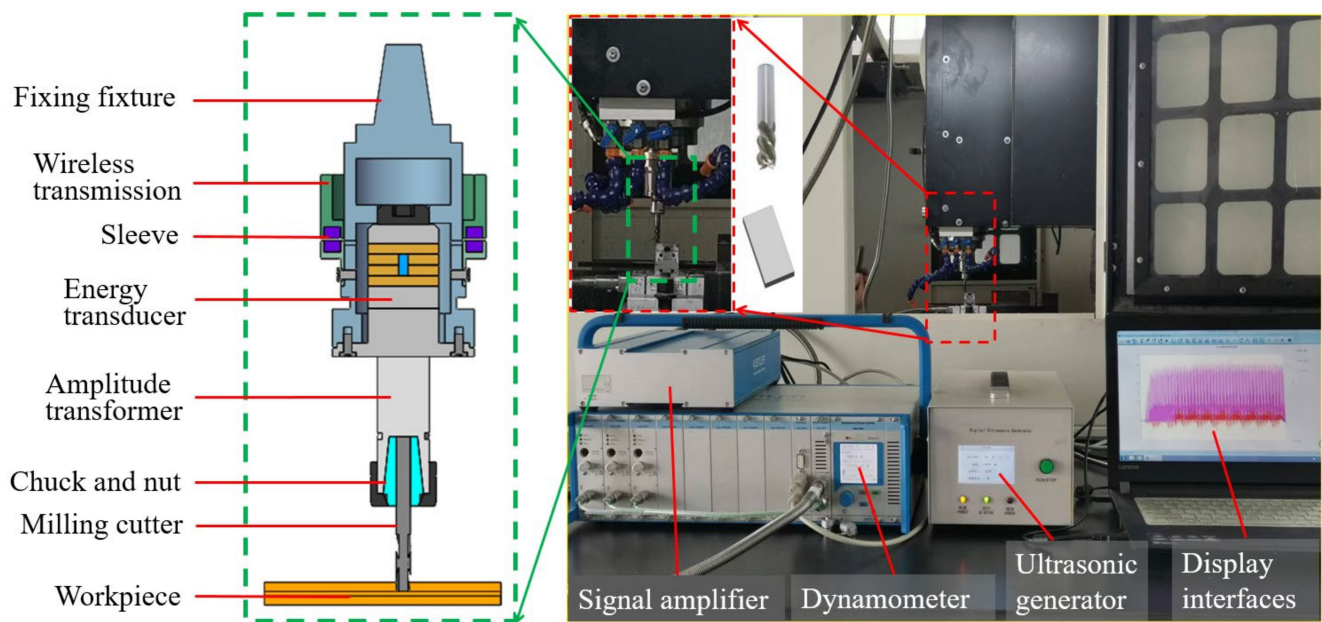


Figure 2. Experimental setup.

Table 1. TC4 Alloy Mechanical Properties. (Test Conditions: 20 °C, Annealing State, 20 mm Diameter Bar Material).

Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Section Shrinkage (%)
967	860	16.2	44.1

In the ultrasonic milling process, to reduce the adverse effects of the tool on the ultrasonic milling effect, the milling cutter should have good thermal conductivity and chip removal performance, and low coating-material activity. This study used a four-blade integral universal hard alloy circular-arc end mill (Zhuzhou Cemented Carbide Cutting Tools Co., Ltd., model: TM-3R-D6.0 R0.5, Zhuzhou, China). The milling cutter specifications were as follows: diameter of 6 mm, blade length of 20 mm, total length of 60 mm, and an AlCrXN coating. The overhang of the tool after clamping was 36 mm.

2.3. Experimental Design

Many factors affect the milling of TC4 titanium alloy to obtain the optimal combination of cutting parameters and achieve high-quality processing of ultrasonic-assisted milling. Four parameters were selected for the experiment: cutting speed v_w (marked as A), feed rate f_z (marked as B), cutting depth a_p (marked as C), and ultrasonic amplitude A (marked as D). The experiment is to study the precision and ultra-precision machining methods of titanium alloys, in order to obtain high-performance surface quality; therefore, the selection of experimental parameters such as feed rate and cutting depth should not be too large. Based on the theory of ultrasonic-assisted precision cutting and reference to peer research, the range of processing parameters [40–42] was selected as follows. The cutting speed v_w ranged from 20 to 50 m/min, the range of each tooth feed rate f_z was 0.01 to 0.04 mm/z, the range of cutting depth a_p was 0.2 to 0.5 mm, and the range of ultrasonic amplitude A was 0 to 5 μ m. The relationship between cutting speed and machine tool spindle speed is $v_w = \pi Dn/1000$, where n represents spindle speed, r/min, and D represents the tool diameter, mm. This article uses cutting speed v_w for experimental analysis. The level ranges of the factors are shown in Table 2.

Table 2. Test Factors and Levels.

Levels	A—Cutting Speed v_w (m/min)	B—Feed Rate f_z (mm/z)	C—Cutting Depth a_p (mm)	D—Ultrasonic Amplitude A (μm)
1	20	0.01	0.2	0
2	30	0.02	0.3	1
3	40	0.03	0.4	3
4	50	0.04	0.5	5

To accurately collect the signal of cutting force variation, a piezoelectric crystal force sensor (model Kistler 5080) was set to a collection frequency of 1000 Hz and a collection range of 100 N. The cutting force signals of ultrasonic milling were collected online in real-time scale, and then the steady cutting forces F_x , F_y and F_z in the x , y and z directions were obtained through a signal amplifier.

Referring to the orthogonal table of five factors and four levels based on standards, this experiment was designed as a four-factor and four-level orthogonal experiment (assuming the fifth factor is a null factor), namely, $L_{16}(4^4)$, with a total of 16 experimental groups. The experimental plan and results are presented in Table 3.

Table 3. Orthogonal Test Results.

No.	A— v_w (m/min)	B— f_z (mm/z)	C— a_p (mm)	D— A (μm)	F_x (N)	F_y (N)	F_z (N)	R_a (μm)
1	20	0.01	0.2	0	8.67	3.63	15.62	0.52
2	20	0.02	0.3	1	17.99	5.38	24.59	0.4
3	20	0.03	0.4	3	29.33	7.81	32.00	0.48
4	20	0.04	0.5	5	40.69	12.21	32.66	0.51
5	30	0.01	0.3	3	11.67	4.44	17.72	0.38
6	30	0.02	0.2	5	10.68	3.20	16.37	0.30
7	30	0.03	0.5	0	35.30	8.28	34.47	0.56
8	30	0.04	0.4	1	34.33	9.65	35.65	0.57
9	40	0.01	0.4	5	14.62	3.55	18.30	0.31
10	40	0.02	0.5	3	27.78	5.21	30.09	0.35
11	40	0.03	0.2	1	15.84	4.96	25.34	0.48
12	40	0.04	0.3	0	27.74	7.96	33.62	0.58
13	50	0.01	0.5	1	18.76	3.03	24.09	0.61
14	50	0.02	0.4	0	23.21	4.30	29.06	0.62
15	50	0.03	0.3	5	22.03	5.61	26.38	0.35
16	50	0.04	0.2	3	18.31	5.46	25.46	0.39

3. Results

3.1. Analysis of Variance of Average Cutting Force

By conducting a variance analysis (ANOVA) on the average cutting force of each group and direction in Table 3 through an orthogonal experiment, the respective results were obtained and are summarized in Tables 4–6. The Fisher distribution test was used to test the significance of variance. The F-distribution was proposed by British statistician Sir Ronald A. Fisher in 1924, it has a wide range of applications in statistics and is the foundation of analysis of variance [43]. Given a degree of freedom of three (i.e., $\text{DoF} = 3$) for the four-factor and four-level orthogonal experiment and a 95% correlation as the standard for strength testing, according to the F distribution critical value $F_{0.05}(3, 3) = 9.28$, the feed rate f_z and cutting depth a_p had a significant impact on the cutting force in the x -axis direction, as shown in Table 4. Moreover, it can be seen from Table 5 that the feed rate f_z had a significant impact on the cutting force in the y -axis direction. Finally, Table 6 shows that the feed rate f_z , cutting depth a_p , and ultrasonic amplitude A had a significant impact on the cutting force in the z -axis direction. Based on the analysis results of Tables 4–6, the feed rate f_z and cutting depth a_p significantly impacted the cutting force. In contrast, the impact

of ultrasonic amplitude A on the cutting force was concentrated in the z -axis direction, which was consistent with the ultrasonic vibration applied in the main spindle z -direction.

Table 4. Milling Force F_x Significance Analysis.

Variance Source	DoF	Sum of Squared Deviations	F	Significance
v_w (m/min)	3	30.405	3.583	
f_z (mm/z)	3	635.684	74.901	1
a_p (mm)	3	657.992	77.529	1
A (μ m)	3	10.967	1.292	
Error	3	8.49		

Table 5. Milling Force F_y Significance Analysis.

Variance Source	DoF	Sum of Squared Deviations	F	Significance
v_w (m/min)	3	15.983	7.129	
f_z (mm/z)	3	64.038	28.563	1
a_p (mm)	3	17.387	7.755	
A (μ m)	3	0.519	0.231	
Error	3	2.24		

Table 6. Milling Force F_z Significance Analysis.

Variance Source	DoF	Sum of Squared Deviations	F	Significance
v_w (m/min)	3	1.412	0.434	
f_z (mm/z)	3	388.881	119.435	1
a_p (mm)	3	216.591	66.521	1
A (μ m)	3	52.317	16.068	1
Error	3	3.26		

3.2. Effects of Different Factors on the Average Cutting Force

Under CM and LUAM conditions, the experimental F_z values were measured through force sensors, as shown in Figure 3. LUAM could significantly reduce the cutting force. Figure 3a compares the 7th group (CM) and the 10th group (LUAM) experiments. Increasing the milling speed and feed per tooth during CM will increase F_z . In contrast, during LUAM, the periodic contact and separation characteristics between the cutting edge and the workpiece during the rotation of the cutter teeth reduced the total contact time between the tool and the workpiece, thereby reducing the overall peak value of the cutting force. In Figure 3c, the 12th group (CM) and the 15th group (LUAM) experiments were compared, and the significant effect of reducing the milling force F_z was still evident. As seen in Figure 3a,c, LUAM reduced the milling peak force F_z by 13.40% and 11.15%, respectively, with an average of 12.28%.

Using the Taguchi method, the cutting forces F_x , F_y , and F_z results were analyzed, as shown in Tables 7–9, respectively. The most significant factors controlling the cutting force F_x were ranked as follows: C (cutting depth) > B (feed rate) > A (cutting speed) > D (ultrasonic amplitude). The optimal combination of cutting parameters in the x -direction was $A_4B_1C_1D_2$. The impacts of milling parameters on the cutting force F_y had the following decreasing order: B (feed rate) > C (cutting depth) > A (cutting speed) > D (ultrasonic amplitude). The optimal combination of cutting parameters in the y -direction was $A_4B_1C_1D_4$. The impacts of milling parameters on the cutting force F_z had the following decreasing order: B (feed rate) > C (cutting depth) > D (ultrasonic amplitude) > A (cutting speed). The optimal combination of cutting parameters in the z -direction was $A_2B_1C_1D_4$.

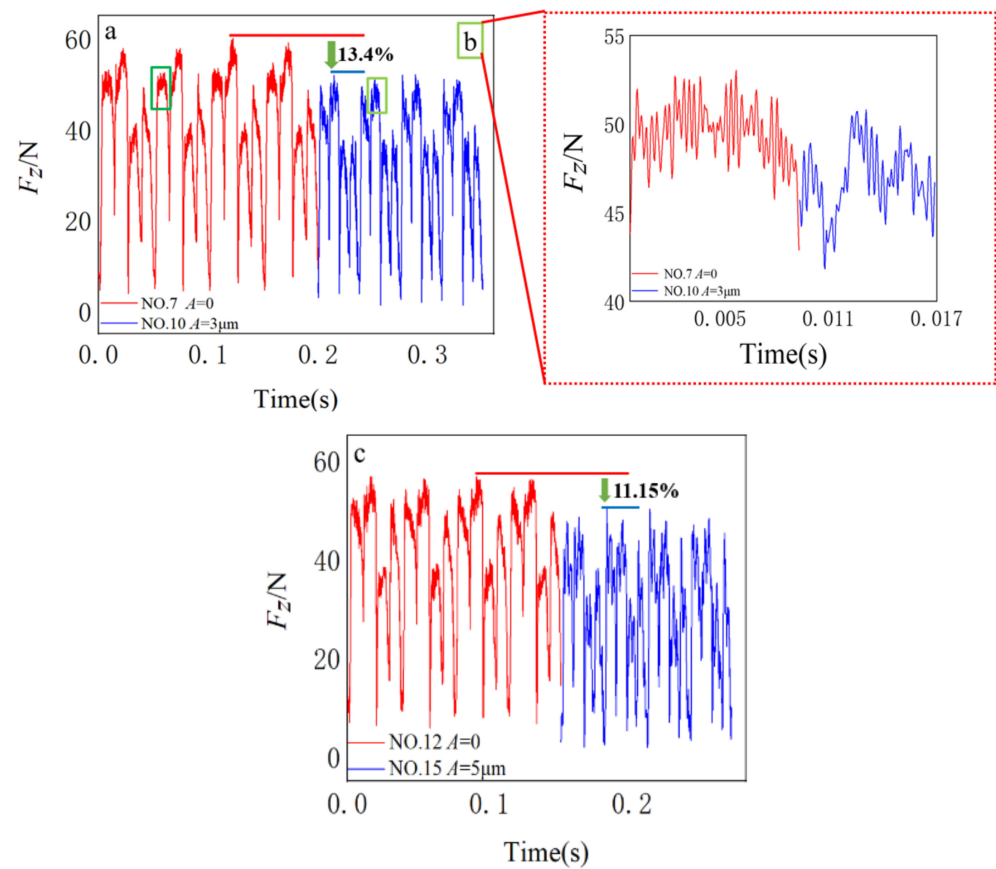


Figure 3. Milling force signal acquisition diagram. (a) Comparison of F_z signals between CM ($A = 0 \mu m$) and LUAM ($A = 3 \mu m$) tests; (b) Comparison of local amplification of CM ($A = 0 \mu m$) and LUAM ($A = 3 \mu m$) Tests F_z in the same period; (c) Comparison of F_z signals between CM ($A = 0 \mu m$) and LUAM ($A = 5 \mu m$) tests.

Table 7. Milling Force F_x Range Analysis Results.

Measured Value	A— v_w (m/min)	B— f_z (mm/z)	C— a_p (mm)	D— A (μm)
K_1	24.173	13.429	13.375	23.732
K_2	22.993	19.916	19.859	21.730
K_3	21.496	25.628	25.373	21.772
K_4	20.578	30.267	30.633	22.006
Range	3.595	16.838	17.258	2.002
Priority of factors	$a_p > f_z > v_w > A$			
Optimal combination	$A_4 B_1 C_1 D_2$			

Table 8. Milling Force F_y Range Analysis Results.

Measured Value	A— v_w (m/min)	B— f_z (mm/z)	C— a_p (mm)	D— A (μm)
K_1	7.255	3.661	4.312	6.043
K_2	6.391	4.522	5.846	5.752
K_3	5.420	6.665	6.329	5.728
K_4	4.601	8.818	7.180	5.143
Range	2.654	5.157	2.868	0.415
Priority of factors	$f_z > a_p > v_w > A$			
Optimal combination	$A_4 B_1 C_1 D_4$			

Table 9. Milling Force F_z Range Analysis Results.

Measured Value	A— v_w (m/min)	B— f_z (mm/z)	C— a_p (mm)	D— A (μ m)
K_1	26.217	18.931	20.697	28.192
K_2	26.051	25.028	25.575	27.417
K_3	26.836	29.545	28.753	26.318
K_4	26.248	31.848	30.426	23.426
Range	0.785	12.917	9.631	4.766
Priority of factors	$f_z > a_p > A > v_w$			
Optimal combination	$A_2B_1C_1D_4$			

Figure 4 shows the effects of various cutting parameters on cutting forces F_x , F_y , and F_z . As seen in Figure 4a, with increasing cutting speed v_w , F_x has a decreasing trend. Figure 4b,c show that with increasing feed per tooth f_z and cutting depth a_p , F_x has an increasing trend. According to Figure 4d, with the addition of ultrasonic vibration F_x exhibits a significant decrease, but with increasing amplitude A the change in F_x is insignificant. As shown in Figure 4e–g, within a certain range, the cutting force F_y drops significantly with increasing cutting speed v_w and grows with increasing feed per tooth f_z and cutting depth a_p . As seen in Figure 4h, with the addition of ultrasonic vibration, F_y drops sharply, and with increasing amplitude A , it shows a significant decreasing trend. In Figure 4i, due to the longitudinal vibration of the tool edge, the effect of cutting speed v_w on the cutting force F_z is insignificant. In Figure 4j,k, the cutting force F_z grows significantly with increasing feed per tooth f_z and cutting depth a_p . In Figure 4l, with increasing amplitude A , F_y shows a significant decreasing trend.

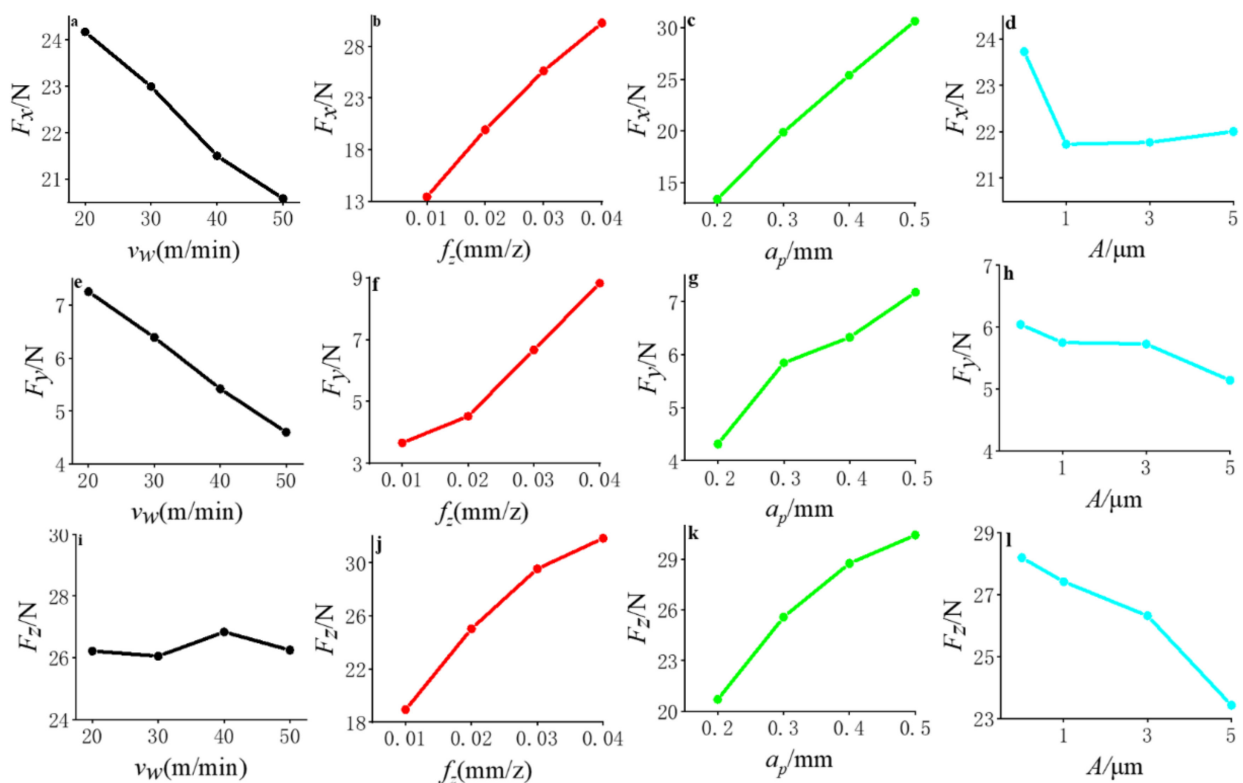


Figure 4. Effects of various milling parameters on cutting forces F_x , F_y and F_z . (a) Relationship curve between cutting speed v_w and cutting force F_x ; (b) Relationship curve between feed rate f_z and cutting force F_x ; (c) Relationship curve between cutting depth a_p and cutting force F_x ; (d) Relationship curve between ultrasonic amplitude A and cutting force F_x ; (e) Relationship curve between cutting speed v_w

and cutting force F_y ; (f) Relationship curve between feed rate f_z and cutting force F_y ; (g) Relationship curve between cutting depth a_p and cutting force F_y ; (h) Relationship curve between ultrasonic amplitude A and cutting force F_y ; (i) Relationship curve between cutting speed v_w and cutting force F_z ; (j) Relationship curve between feed rate f_z and cutting force F_z ; (k) Relationship curve between cutting depth a_p and cutting force F_z ; (l) Relationship curve between ultrasonic amplitude A and cutting force F_z .

3.3. Surface Roughness Analysis of Orthogonal Test Results

3.3.1. Surface Roughness Analysis

The variance analysis (ANOVA) of the surface roughness Ra of the processed workpieces is shown in Table 10.

Table 10. Surface Roughness Significance Analysis.

Variance Source	Sum of Squares of Deviations	DoF	F Value	Significance
v_w (m/min)	0.009	3	0.500	1
f_z (mm/z)	0.018	3	1.000	
a_p (mm)	0.024	3	1.333	
A (μm)	0.109	3	6.056	
Error	0.02	3		

For DoF = 3, from a four-factor, four-level orthogonal experiment, the confidence level was 95%; according to the critical value of the F distribution $F_{0.05}(3, 3) = 5.39$, it can be seen from the variance analysis results on the roughness that the ultrasonic amplitude had a significant impact on the surface roughness of the workpiece, and the milling rotation rate had the weakest impact. To further explore the effect of different milling parameters on the surface roughness of the processed workpieces, range analysis was performed on the surface roughness Ra of the workpieces, as shown in Table 11. The effect of ultrasonic amplitude on surface roughness was dominant, and the surface roughness is greatly affected by changes in ultrasonic amplitude.

Table 11. Surface roughness extreme analysis.

Measured Value	A— v_w (m/min)	B— f_z (mm/z)	C— a_p (mm)	D— A (μm)
K_1	0.450	0.427	0.395	0.542
K_2	0.453	0.417	0.427	0.515
K_3	0.430	0.468	0.495	0.400
K_4	0.493	0.513	0.507	0.368
Range	0.063	0.096	0.112	0.174
Priority of factors	$A > a_p > f_z > v_w$			
Optimal combination	$A_3B_2C_1D_4$			

The analyses of the orthogonal level results on surface roughness in Tables 10 and 11 revealed the primary and secondary effects of each milling parameter on the surface roughness of the workpiece, ranking them as follows: D (ultrasonic amplitude) > C (cutting depth) > B (feed rate) > A (cutting speed).

3.3.2. Effects of Various Milling Parameters on Surface Roughness

Patterns of various milling parameters' effects on the average surface roughness of the processed workpieces are shown in Figure 5. In Figure 5a, as the cutting speed increased, the surface roughness of the workpiece was the lowest at a cutting speed of 40 m/min. When the cutting speed is higher than 40 m/min, the impact and friction between the rear face of the milling cutter and the machined surface become more severe under the action of high-frequency vibration, resulting in a rapid increase in surface roughness. In Figure 5b, as the feed rate f_z increased, the roughness first gradually dropped, reaching its

minimum at $f_z = 0.02$ mm/z, and then grew sharply; the reason is also due to the intensified interaction between the tool and the machined surface. As seen in Figure 5c, as the milling depth increased, the surface roughness of the workpiece grew insignificantly (by only 0.12). In Figure 5d, during the amplitude range from 0 to 5 μm , compared with CM, the LUAM reduced surface roughness, but as the ultrasonic amplitude increased, the trend of reducing surface roughness was saturated.

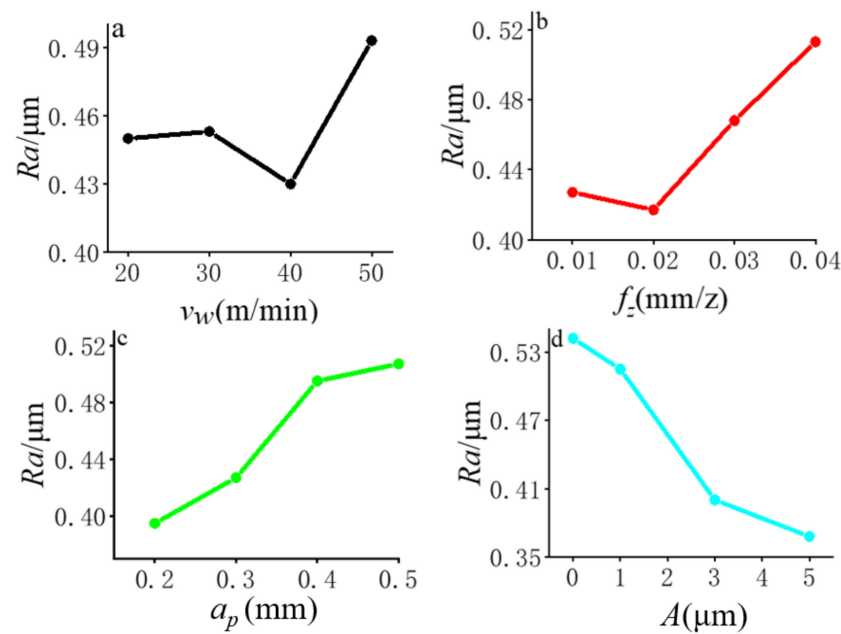


Figure 5. Effects of various milling parameters on surface roughness. (a) Relationship curve between cutting speed v_w and surface roughness R_a ; (b) Relationship curve between feed rate f_z and surface roughness R_a ; (c) Relationship curve between cutting depth a_p and surface roughness R_a ; (d) Relationship curve between ultrasonic amplitude A and surface roughness R_a .

3.4. Surface Morphology

The surface morphology of LUAM was examined and analyzed using a desktop scanning electron microscope (model COXEM EM-30 PLUS, resolution of 5 nm@30 kV SE). The SEM surface morphologies obtained by increasing the amplitude A at a 1000 $\times$ magnification are shown in Figure 6.

In Figure 6a, corresponding to test 14 in Table 3, the surface morphology of TC4 titanium alloy milled by CM shows a banded linear texture along the tool path, with a surface roughness of 0.62 μm . Figure 6b, corresponding to test 11 in Table 3, shows the result of LUAM with $A = 1$ μm ; the surface microstructure of the workpiece is arranged in a certain regular alternating distribution along the tool feed direction, with a surface roughness of 0.48 μm . In Figure 6c, corresponding to test 3 in Table 3, LUAM with $A = 3$ μm , the surface texture has a tight “sine/cosine” structure, in contrast to CM. After increasing amplitude A , the texture is weakened, and the surface texture becomes ridge-shaped and arranged regularly along the tool path, with a surface roughness of 0.48 μm . In Figure 6d, corresponding to test 6 in Table 3, LUAM with $A = 5$ μm , surface roughness is 0.3 μm , the “sine/cosine” texture on the surface of the workpiece is denser, and the surface texture is also changed, showing a regular arrangement of a fish scale-like texture. The high-frequency vibration generated by LUAM repeatedly squeezes the cutting surface to produce a texture which is conducive to chip separation and avoids chip adhesion on the workpiece surface, improving the workpiece surface quality.

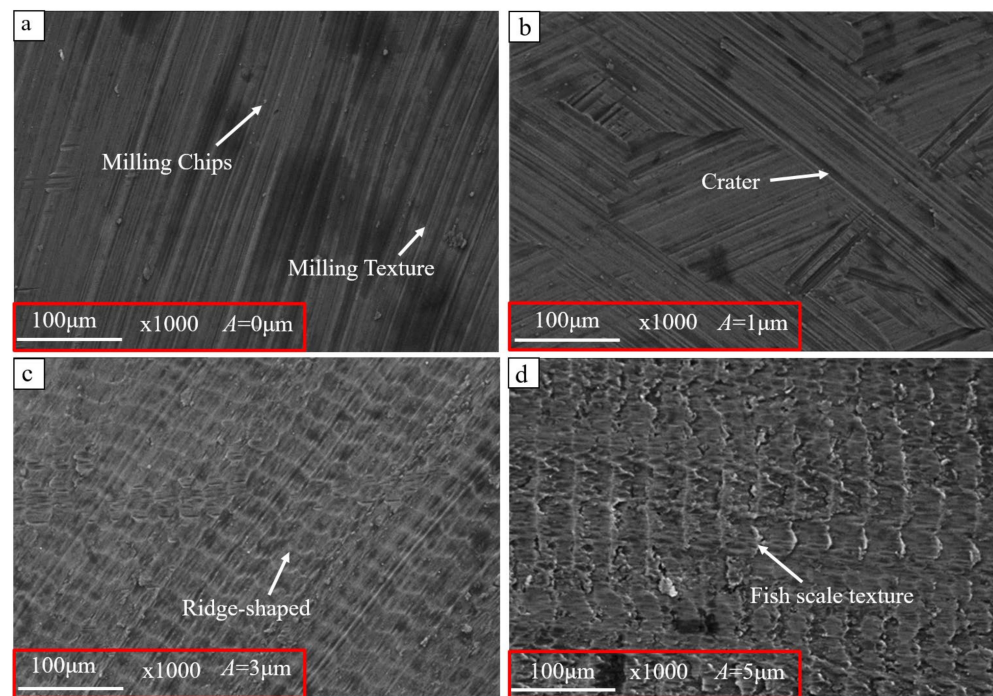


Figure 6. LUAM microsurface topography. (a) Surface morphology at CM ($A = 0 \mu\text{m}$); (b) Surface morphology at ultrasonic amplitude $A = 1 \mu\text{m}$; (c) Surface morphology at ultrasonic amplitude $A = 3 \mu\text{m}$; (d) Surface morphology at ultrasonic amplitude $A = 5 \mu\text{m}$.

3.5. Microstructure of the Cutting Section

After hard cutting at high temperature, high pressure, and high strain, the surface microstructure and subsurface matrix structure of the sample have undergone significant changes, as shown in Figure 7.

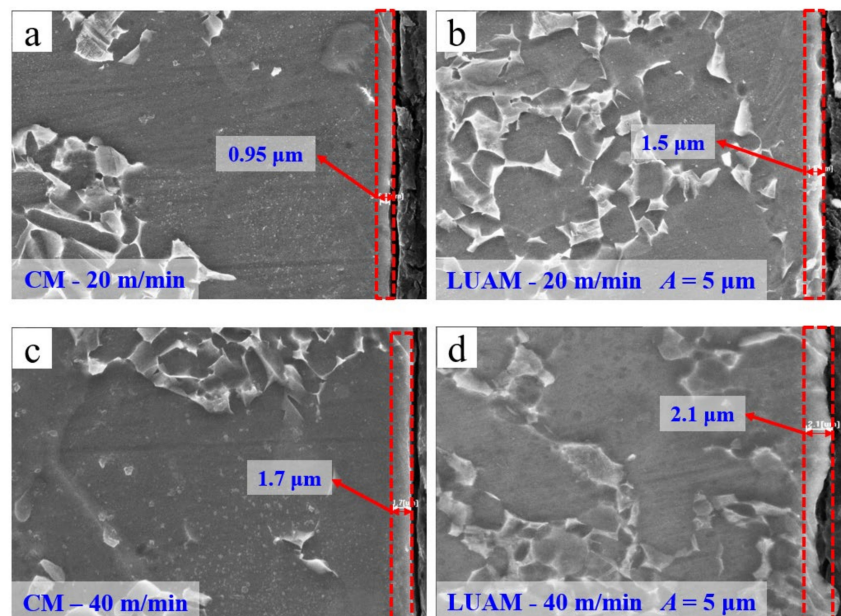


Figure 7. Effects of high and low rotation speeds on the surface microstructure deformation layer under CM and LUAM conditions. (a) Deformation layer depth under CM-processed ($v_w = 20 \text{ m/min}$); (b) Deformation layer depth under LUAM-processed ($v_w = 20 \text{ m/min}$, $A = 5 \mu\text{m}$); (c) Deformation layer depth under CM-processed ($v_w = 40 \text{ m/min}$); (d) Deformation layer depth under LUAM-processed ($v_w = 40 \text{ m/min}$, $A = 5 \mu\text{m}$).

The cutting surfaces of CM- and LUAM-processed workpieces had a significant white surface layer. At a lower cutting speed ($v_w = 20$ m/min), there are slight differences in the microstructure of the surface layer and the substrate layer. At a higher cutting speed ($v_w = 40$ m/min), there is a significant difference in the microstructure between the processed surface layer and the substrate layer. The surface layer forms a severe plastic deformation layer with a certain depth. The surface layer material of the workpiece undergoes severe grain deformation, with grains elongated and refined along the cutting direction, resulting in irregular microstructure. At $v_w = 40$ m/min, the deformation layer depth of the LUAM-processed workpiece can reach $2.1\text{ }\mu\text{m}$. However, there are no defects on the surface at lower cutting speed. Further analysis shows that as the cutting speed increases, the friction between the tool and the processed surface grows, and the deformation layer depths of both the CM- and LUAM-processed workpiece increase. At the same speed, the depth of the deformation layer on the surface of the LUAM-processed workpiece is slightly greater than the CM-processed workpiece, as shown in Figure 7d. The experiment shows that after the superposition of ultrasonic vibration, the high-frequency impact effect of the tool on the processed surface increases the depth of the deformation layer.

3.6. Experimental Verification

To verify the optimal combinations obtained from the orthogonal experimental analysis, including $A_4B_1C_1D_2$, $A_4B_1C_1D_4$, $A_2B_1C_1D_4$, and $A_3B_2C_1D_4$, four experiments were conducted with these combinations, as shown in Table 12. The cutting forces in the x , y , and z directions were obtained when the cutting was stable, and the surface roughness of the workpiece was measured. The optimal combinations in the x -, y -, and z -directions achieved average cutting forces of 7.35, 2.88, and 13.26 N, respectively. The optimal combination for surface roughness achieved a minimum value of $0.29\text{ }\mu\text{m}$.

Table 12. Test Results for the Optimal Combinations $A_4B_1C_1D_2$, $A_4B_1C_1D_4$, $A_2B_1C_1D_4$, and $A_3B_2C_1D_4$.

No	A— v_w (m/min)	B— f_z (mm/z)	C— a_p (mm)	D— A (μm)	F_x (N)	F_y (N)	F_z (N)	Ra (μm)
V1	50	0.01	0.2	1	7.35	3.24	15.22	0.52
V2	50	0.01	0.2	5	9.35	2.88	16.71	0.33
V3	30	0.01	0.2	5	9.73	3.57	13.26	0.39
V4	40	0.01	0.2	5	9.57	3.40	17.14	0.29

By comparing the minimum values of the CM test in Table 3 and the LUAM test in Table 12, the minimum value for F_x in Table 3 was found to be 8.67 N (Test 1), compared with the minimum value for F_x of 7.35 N (Test V1) in Table 12. The average cutting force in x -axis direction decreased by 15.22%; the F_y minimum in Table 3 was 3.63 N (Test 1), and the F_y minimum in Table 12 was 2.88 N (Test V2), with a 20.66% reduction in the y -axis mean cutting force. The F_z minimum in Table 3 was 15.62 N (Test 1), the F_z minimum in Table 12 was 13.26 n (Test V3), and the z -axis average cutting force decreased by 15.11%; the Ra minimum was $0.52\text{ }\mu\text{m}$ (Test 1) in Table 3, and the Ra minimum was $0.29\text{ }\mu\text{m}$ (Test V4) in Table 12. The average roughness was reduced by 44.23%.

4. Conclusions

This study experimentally investigated the cutting force and surface integrity of TC4 titanium alloy workpiece processed using LUAM. The effects of cutting speed v_w , feed per tooth f_z , cutting depth a_p , and ultrasonic amplitude A on cutting force and surface integrity were comprehensively analyzed. The following conclusions were drawn:

- (1) By comparing CM and LUAM, it was found that applying LUAM can reduce the peak cutting force, due to the periodic high-speed contact and separation between the tool and workpiece, which reduces the cutting force to a certain extent. The average peak cutting force was reduced by 12.28%, effectively improving cutting performance.

- (2) After applying LUAM, the cutting forces in the x , y , and z directions were reduced by 15.22, 20.66, and 15.11%, respectively; the average surface roughness of the workpiece was reduced by 44.23%.
- (3) The LUAM processing of the workpiece significantly improved its surface quality. With increasing ultrasonic amplitude, a regular “sine/cosine” texture appeared on the surface of the workpiece. When this amplitude was increased to a certain degree, a “fish scale-like” texture appeared on the workpiece surface. The increase in ultrasonic amplitude improved the chip separation effect.
- (4) At higher milling/cutting speeds, the crystal lattice of the subprocessed surface material was distorted under the high stress of milling friction, and the grains became elongated and refined along the cutting direction. The irregular microstructure formed a directional plastic deformation layer of a certain depth. Under the same rotation speed, the thickness of the deformation layer of the LUAM-processed workpieces exceeded those of the CM-processed ones.
- (5) Ultrasonic-assisted machining forms regularly distributed surface microstructures, which can effectively store lubricating oil and have great significance for reducing the wear and lubrication of components with mutually moving working surfaces, such as in the manufacturing of high-performance bearings. Precision microtextured surfaces with special functions can be achieved by adjusting parameters such as frequency and amplitude of ultrasonic processing, which is of great significance for constructing wear-resistant and high-strength superhydrophobic surfaces.

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