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The Influence of Ultrasonic Vibration Milling on the Surface Integrity of 3D Printed TA15

Jun Wei [a], Xueming Zhu *

School of Mechanical Engineering, Tianjin University of Technology and Education, Tianjin, China
* Corresponding Author: Xueming Zhu (Email: zhxming85@163.com), [a] 577106894@qq.com

ABSTRACT

Ultrasonic assisted milling technology has shown significant effects in improving the quality of machined surfaces. During ultrasonic milling, while maintaining the same cutting time, changes in the axial ultrasonic vibration amplitude of the tool can cause changes in the height of the surface microstructure contour, which in turn affects the microstructure. Based on the above reasons, different machining surface microstructures can be obtained by changing the axial ultrasonic amplitude of the tool. This article mainly uses surface morphology, hardness, and surface roughness as key indicators to evaluate the integrity of the machined surface. It systematically analyzes the trends and laws of the influence of ultrasonic amplitude and feed rate per tooth on surface morphology, surface hardness, and surface roughness in the process of ultrasonic vibration milling SLM forming TA15 titanium alloy.

KEYWORDS

Selective Laser Melting; TA15; Ultrasonic Milling.

1. INTRODUCTION

Titanium alloys are increasingly used in industries such as aviation, aerospace, marine, and automotive due to their special material properties, such as high strength, excellent corrosion resistance, and thermal capabilities [1-2]. However, the production of titanium alloys presents challenges due to their low thermal conductivity [3], tendency to undergo active chemical reactions with oxygen [4], and susceptibility to strain hardening [5,6]. Traditional methods, such as powder metallurgy[7,8], rolling, casting, and bulk raw material forging, can be used to manufacture titanium alloy products[9]. However, these methods have disadvantages such as complex manufacturing processes, numerous processing steps, long production cycles, high material removal rates, and high manufacturing costs.

This article selects SLM-TA15 alloy as the research object and conducts research based on ultrasonic assisted milling method. Based on milling experiments, the variation laws of surface roughness, surface morphology, and surface layer microhardness with cutting parameters are studied, providing reference for improving milling efficiency, product quality, and standardizing process specifications, which has important guiding significance for practical production.

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2. EXPERIMENTAL DESIGN

After the ultrasonic process parameters were pre-set and calibrated, we selected the required ultrasonic parameter configuration and ensured that the power output of the ultrasonic equipment was constant. The milling parameters are shown in Table 1.

Table 1. Single factor experiments table of ultrasound amplitude

Cutting Speed(rpm)	Feed per Tooth(mm/z)	Cutting Width(mm)	Cutting Depth(mm)	Ultrasonic amplitude (μm)
2000	0.02	0.3	2	1, 2, 3, 4, 5

3. THE INFLUENCE OF ULTRASOUND AMPLITUDE ON SURFACE INTEGRITY

3.1. The Influence of Ultrasonic Amplitude on Surface Morphology

Figure 1 shows the surface morphology after conventional milling and ultrasonic vibration milling. From the surface morphology map, it can be seen that the conventional milling surface has clear feed marks, while the surface of ultrasonic vibration milling presents regular and dense microtextures caused by vibration.

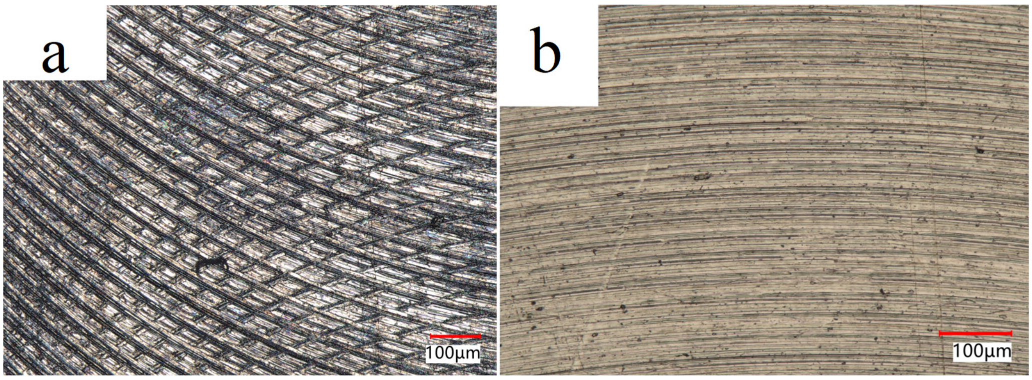

Figure 1. (a) Conventional milling, (b) Surface morphology after ultrasonic vibration milling

Observing Figure 2, some visible small chips adhere to the surface after conventional milling. As shown in Figure 2 (a), the surface microtexture is not obvious with an ultrasonic amplitude of 1 μ m. The milling surface with an ultrasonic amplitude of 2 μm also adheres to some visible small chips, and small and dispersed surface microtextures appear. However, when the ultrasonic amplitude exceeds 3 μm, the chip adhesion phenomenon basically disappears, and is replaced by a surface morphology formed by the vibration trajectory of the cutting edge, with significant plastic deformation characteristics, including plowing grooves and separation ridges, and these surfaces are densely covered with regular microtextures.

By carefully observing the surface characteristics after ultrasonic vibration milling, it can be seen from the details in Figure 3 that when the ultrasonic amplitude is 2 μm, the fluctuation caused by the vibration of the tool leaves obvious ultrasonic machining marks on the machined surface. When the amplitude increased to 4 μm, significant milling cutter cutting edge impact and ironing marks appeared on the surface. The impact and ironing of milling cutter cutting edges can actually improve the quality of the machined surface, making the microstructure clearer and more distinguishable, as shown in Figure 3 (d).

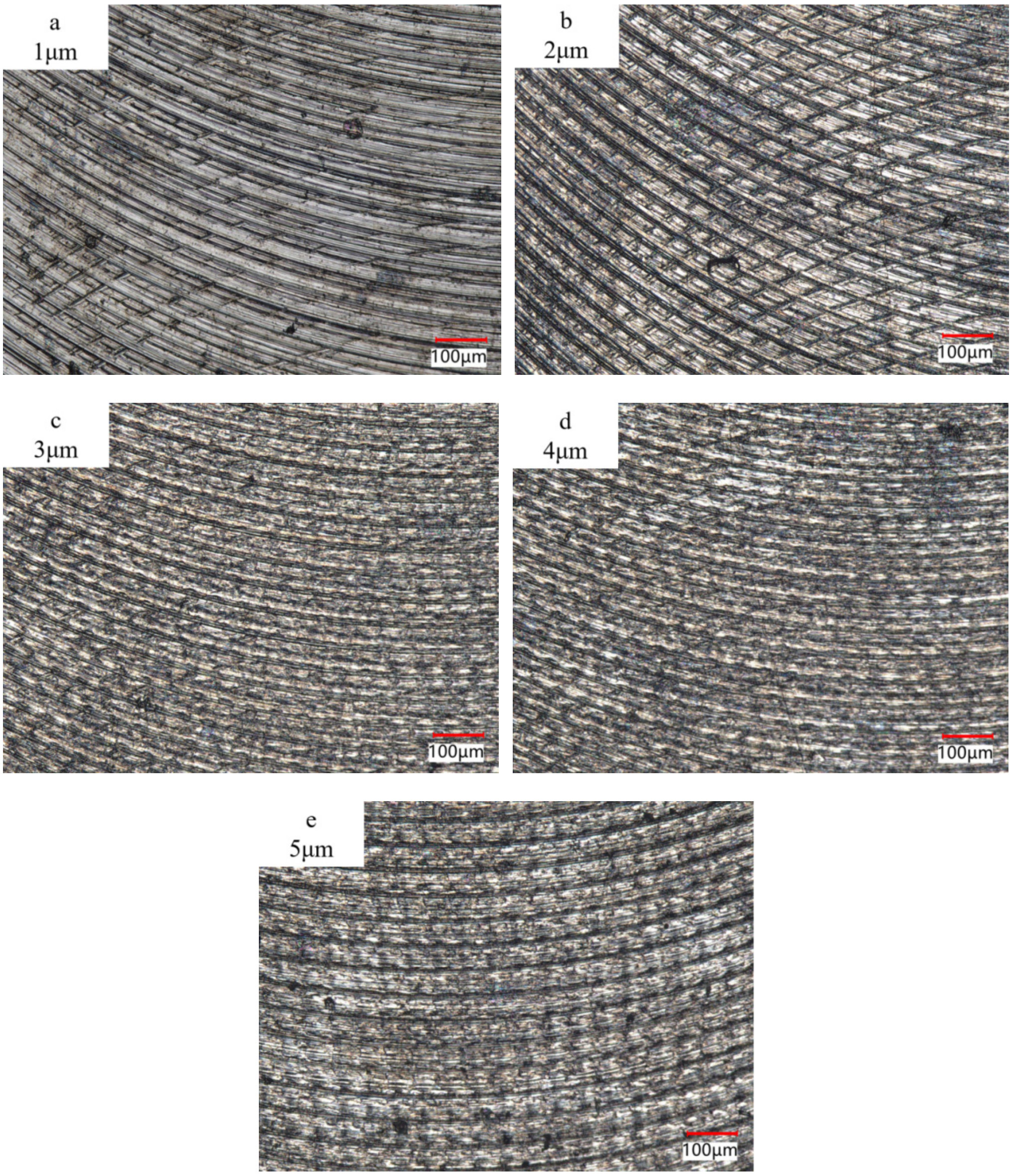

Figure 2. Surface morphology magnified 100 times after ultrasonic vibration milling

3.2. The Influence of Ultrasonic Amplitude on Surface Roughness

Each group of samples was measured at three positions, and the average of the three measurement results was taken for analysis. Figure 4 shows the roughness measurement of conventional milling and ultrasonic vibration milling under different amplitudes. Figure 5 shows the Sa values of the machined surface under conventional milling and ultrasonic vibration milling under different amplitudes.

As shown in Figure5, the Sa value of the surface milled by ultrasonic vibration is larger than that of conventional milling, and this value first increases and then decreases with the increase of ultrasonic amplitude, reaching a peak of 0.493μm at an amplitude of 3μm, an increase of 26.41% compared to conventional milling. Analyzing the possible reasons, at a low amplitude of 2μm, the microstructure formed on the processed surface is small and dispersed, resulting in a relatively low Sa value; When the amplitude rises to 3μm, the cutting depth change caused by vibration of the tool intensifies, and the partially excised part protrudes, forming small burrs, resulting in a significant increase in Sa value. However, under high amplitude conditions of 4μm and 5μm, the ironing effect of the milling cutter bottom edge on the surface during cutting is enhanced, effectively reducing the surface Sa value. This phenomenon is also intuitively confirmed in the surface morphology images of Figure 2 and Figure 3.

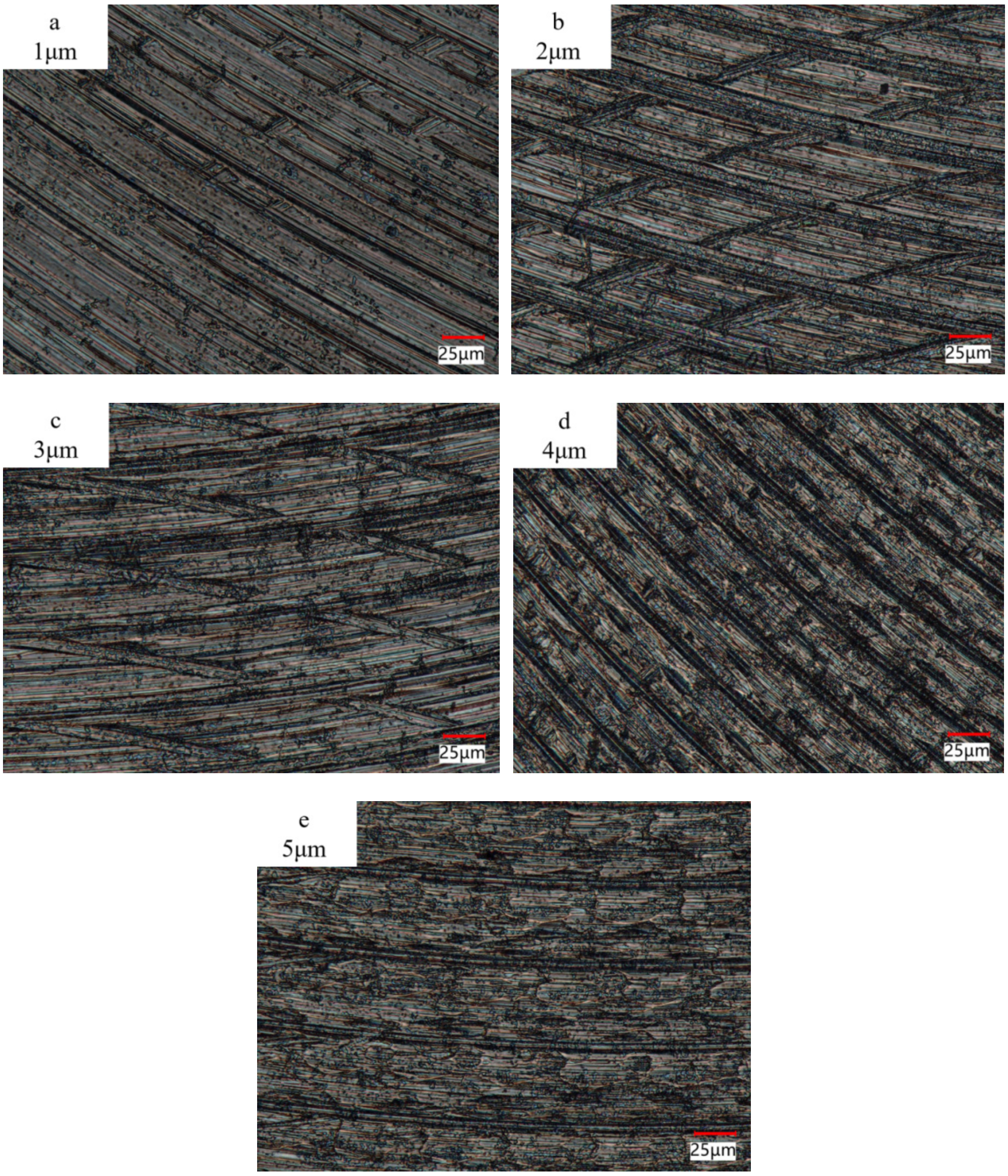

Figure 3. Surface morphology magnified 500 times after ultrasonic vibration milling

3.3. The Effect of Ultrasonic Amplitude on Hardness

Table 2 lists the surface hardness measurement data of conventional milling and ultrasonic vibration end face milling. The average value of three measurements was taken for each group of samples for evaluation. Figure6 visually illustrates the relationship between ultrasound amplitude and surface hardness.

According to the analysis of Figure6, under specific cutting parameters, ultrasonic vibration milling can significantly improve the hardness of the machined surface, and the hardness value increases with the increase of ultrasonic amplitude, surpassing the hardness of conventional milling (308.73HV). This indicates that ultrasonic vibration cutting technology can effectively enhance surface hardness, and the increase in amplitude further promotes the improvement of hardness. The reason is that an increase in amplitude means an increase in ultrasonic energy acting on the machined surface, making the separation effect of vibration milling more prominent. During this process, the impact and ironing effect of the milling cutter's bottom edge on the machined surface intensify, resulting in an increase in surface hardness. When the ultrasonic amplitude reaches 5μm, the surface hardness increases to 360.25HV, which is 18.83% higher than conventional milling.

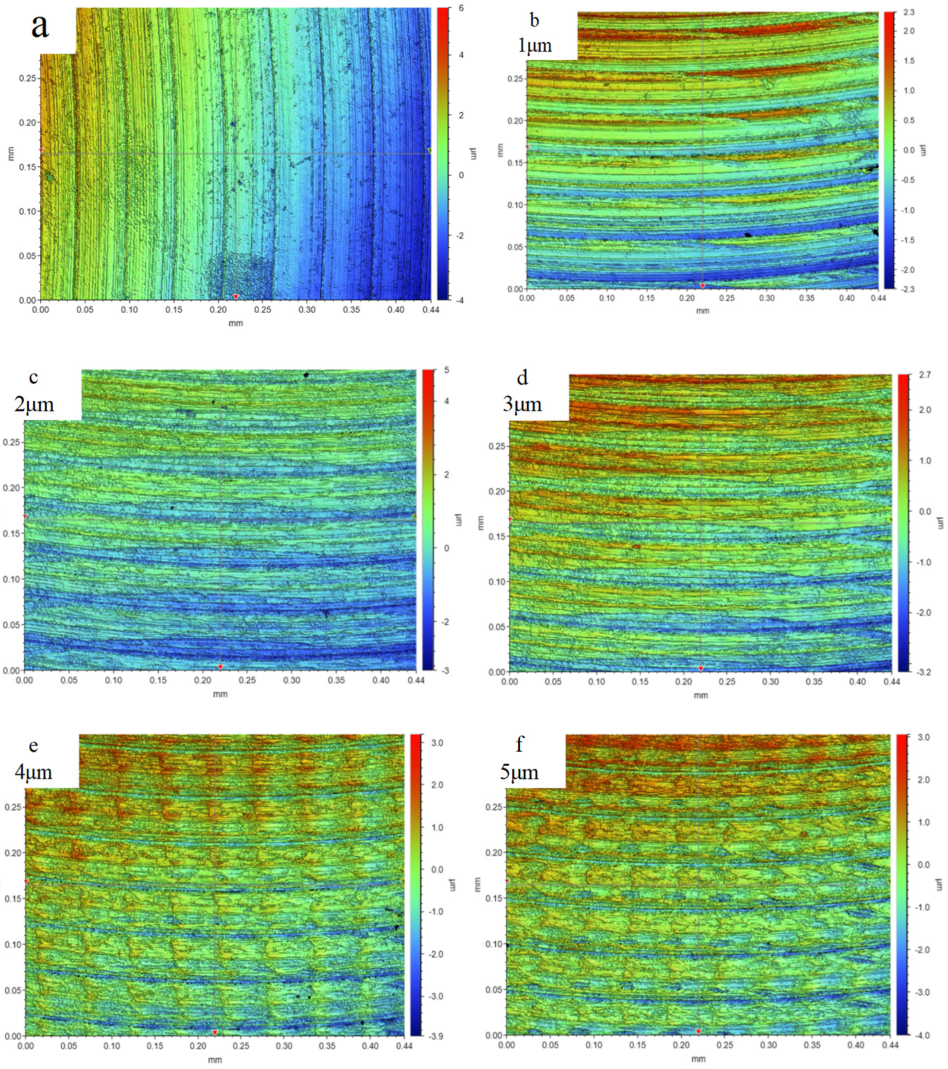

Figure 4. Surface roughness under different ultrasonic amplitudes (a) Conventional milling, fz=0.02mm/z，((b)A=1um,(c)A=2μm,(d)A=3um，(e)A=4μm,(f)A=5um

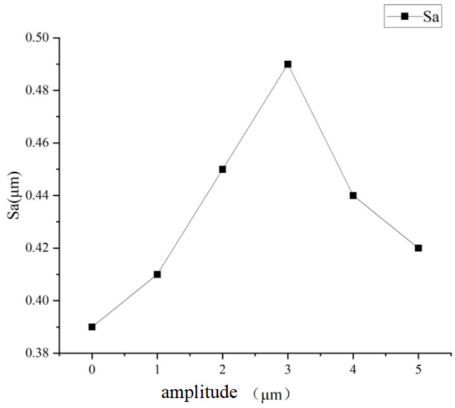

Figure 5. Influence of Ultrasonic Amplitude on Sa Value of Processed Surface

Table 2. Surface Hardness Measurement Values under Different Ultrasonic Amplitude

hardness（HV）				
	first	second	third	average
Conventional milling	307.67	309.42	309.10	308.73
1μm	316.97	319.34	322.07	313.46
2μm	327.24	325.38	323.25	325.29
3μm	340.32	335.71	340.70	338.91
4μm	344.76	348.56	350.17	347.83

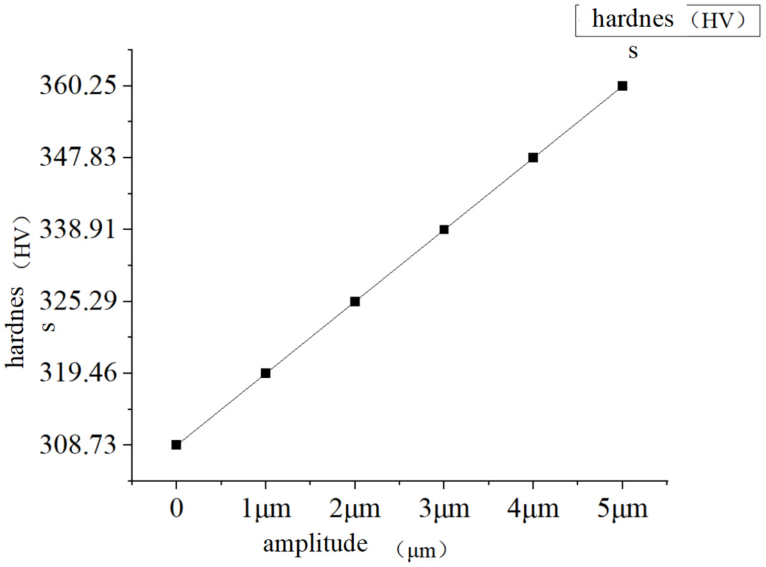

Figure 6. Effect of Ultrasonic Amplitude on Surface Hardness during Machining

4. SUMMARY

When the ultrasonic amplitude is 2μm, the fluctuation caused by the vibration of the tool leaves obvious ultrasonic machining marks on the machined surface. When the amplitude increased to 4μm, significant milling cutter cutting edge impact and ironing marks appeared on the surface. The impact and ironing of milling cutter cutting edges can actually improve the quality of the machined surface, making the microstructure clearer and more distinguishable.

The Sa value of ultrasonic vibration milling surface is larger than that of conventional milling, and this value first increases and then decreases with the increase of ultrasonic amplitude. At a low amplitude of 2μm, the micro texture formed on the machined surface is small and dispersed, so the Sa value is relatively low; When the amplitude rises to 3μm, the cutting depth change caused by vibration of the tool intensifies, and the partially excised part protrudes, forming small burrs, resulting in a significant increase in Sa value. However, under high amplitude conditions of 4μm and 5μm, the ironing effect of the milling cutter bottom edge on the surface during cutting is enhanced, effectively reducing the surface Sa value.

Ultrasonic vibration cutting technology can effectively enhance surface hardness. An increase in amplitude means an increase in ultrasonic energy acting on the machined surface, making the separation effect of vibration milling more prominent. During this process, the impact and ironing effect of the milling cutter's bottom edge on the machined surface intensify, resulting in an increase in surface hardness.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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