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Analysis of the Surface Friction and Wear Properties of High Temperature γ-TiAl Alloy in Ultrasonic-Assisted Milling

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ABSTRACT

γ-TiAl alloy, with its excellent creep resistance, oxidation resistance, and corrosion resistance, is regarded as one of the most promising materials in high - end fields such as aerospace. In aerospace and other fields, the requirements for the surface friction and wear performance of components are extremely stringent. However, the surface properties after traditional processing have limitations. Therefore, it is of great significance to seek more excellent processing methods to improve the friction and wear characteristics of the material. In this paper, ultrasonic - assisted high - temperature milling was carried out on the γ-TiAl cladding layer prepared by the laser directed energy deposition technology and the γ-TiAl castings, and the friction and wear performance of the machined surfaces was analyzed. The experimental results indicate that, compared with castings, the cladding layer has better surface wear resistance due to its smaller internal structure size. In comparison with the surface of the cladding layer processed by conventional machining, the friction coefficient and wear cross-sectional area of the surface processed by ultrasonic machining are reduced by 4.1% and 57.27% respectively, demonstrating that the surface processed by ultrasonic - assisted machining exhibits more excellent friction and wear performance.

KEYWORDS

γ-TiAl Alloy; Laser Cladding; Ultrasonic Assistance; Friction and Wear.

1. INTRODUCTION

Additively manufactured γ-TiAl alloy exhibits tremendous application potential in high-end fields such as aerospace and automotive manufacturing. This is attributed to the alloy's low density, high specific strength, excellent high-temperature properties, as well as the unique processing characteristics of additive manufacturing, including flexibility and cost-effectiveness [1-3]. These application scenarios are typically characterized by complex working conditions involving high temperature, high pressure, and relative motion, which impose high requirements on the friction and wear performance. In the key components of automotive engines, the friction and wear performance of TiAl alloy is directly related to the stability of the engine's power output and its service life. However, additively manufactured workpieces suffer from issues such as internal structural defects and relatively low surface manufacturing precision. Therefore, corresponding post-processing is required to ensure that the workpieces meet the service conditions.

Considering the inherent brittleness of γ-TiAl alloy at room temperature, there are currently many special processing methods for difficult-to-machine materials, such as ultrasonic-assisted machining [4] and thermal-assisted machining [5]. The advantages of these auxiliary technologies have been demonstrated in brittle and hard materials, including titanium alloys, SiC/Al composites, and ceramic matrix composites [6]. Baoqi Chang [7] conducted experimental on conventional slot milling and ultrasonic-assisted slot milling of titanium alloys. The results show that compared with conventional machining, ultrasonic-assisted machining reduces material spalling and edge chipping, and at the same time, the side walls of the slots are smooth and the edge profiles are regular. Ji-an Duan [8] carried out longitudinal-torsional ultrasonic vibration milling of GH4169 superalloy and found that after ultrasonic machining, the friction coefficient and wear amount of the surface decreased by up to 18.2% and 15.8% respectively. The regular ultrasonic vibration texture inhibits the friction and growth of contact nodes in the contact area, reducing the degree of surface wear. Uhlmann et al. [9] conducted cutting tests on preheated γ-TiAl alloy. The results show that increasing the temperature can significantly reduce the number and size of cracks. Kim [10] used high-temperature-assisted cutting for titanium alloy and Inconel 718 and found that compared with conventional machining, high-temperature-assisted machining reduces the cutting force and surface roughness during the cutting process and improves the machinability of the materials. Tao Fan [11] used induction heating-assisted machining of γ-TiAl to analyze the machining performance and found that the preheating temperature of 450°C is the optimal temperature, which reduces the cutting force by 35% and the surface roughness by 67.3%. Through the above analysis, it is found that both ultrasonic assistance and thermal assistance can improve the machinability and surface properties of workpieces. However, there are few studies on the friction and wear properties of the surface of the cladding layer after machining. Therefore, this paper studies the friction and wear properties of the surface of high-temperature γ-TiAl alloy under conventional machining and ultrasonic machining conditions, and explores the influence of material properties and ultrasonic vibration on the friction and wear properties of γ-TiAl alloy.

2. EXPERIMENTAL CONDITIONS AND SCHEMES

2.1. Experimental Conditions

The cladding powder is an intermetallic compound of Ti-48Al-2Cr-2Nb with a particle size of 45-105 μm, and the substrate is TC4. The cladding layer is prepared by using the powder-feeding type metal 3D printer (RC-LDM8060) of Nanjing Zhongke Yuchen. The phase analysis is carried out by using a rotating anode X-ray diffractometer. The selected parameters are as follows: the voltage is 40 kV, the current is 150 mA, the scanning speed is 10°/min, and the scanning range is from 20° to 90°.

The experimental device is shown in Figure 1. A longitudinal-torsional horn with a frequency of 35 kHz is compounded onto the machine tool spindle. Before the experiment, the ultrasonic amplitude of the tool tip is calibrated by a laser displacement sensor. The workpiece is clamped on the workbench, and an induction heating coil is used to preheat the workpiece. Taking the influence of temperature into account, a high-temperature-resistant PCD two-edged milling cutter with a diameter of 8 mm is selected. Table 1 presents the experimental scheme.

Table 1. Milling experiment scheme

Cutting speed(m/min)	Feed per tooth (mm/r)	Cutting depth (mm)	Amplitude (μm)	Temperature (°C)	Material
60	0.015	0.15	0	200	Casting
			2		
			0		Clading layer
			2		

The friction and wear experiment were carried out on a friction and wear testing machine (MFT - 5000S). A Si_3N_4 ceramic friction ball with a diameter of 6.35 mm, a precision of G10, and a Rockwell hardness of 91 HRC was selected. The friction frequency adopted in the experiment was 3 Hz, the load was 20 N, and the wear time was 30 minutes. Before and after the experiment, the workpiece was placed in an ultrasonic cleaner filled with an alcohol solution to remove surface impurities and residual wear debris. A super depth - of - field microscope (VHX - 2000, KEYENCE) was used to observe the macroscopic morphology of the worn area, and an Olympus laser confocal microscope (OLS5100, OLYMPUS) was used to observe the three - dimensional morphology of the worn area and measure the cross - sectional area.

Figure 1. Schematic Diagram of the Experimental Device

3. RESULTS

3.1. Phase Analysis of the Material

The results of the metallographic structure and phase analysis of the cladding layer and the casting are shown in Figure 2. By observing the microstructures, it was found that both the cladding layer and the casting were composed of lamellar structures. The cladding layer was mainly composed of the γ-TiAl phase, with small and unevenly distributed tissue sizes, presenting a typical Widmanstätten structure. The phase analysis of the casting revealed that it mainly consisted of the γ-TiAl phase and the incompletely fused pure Al phase, and the morphological structure was relatively uniform.

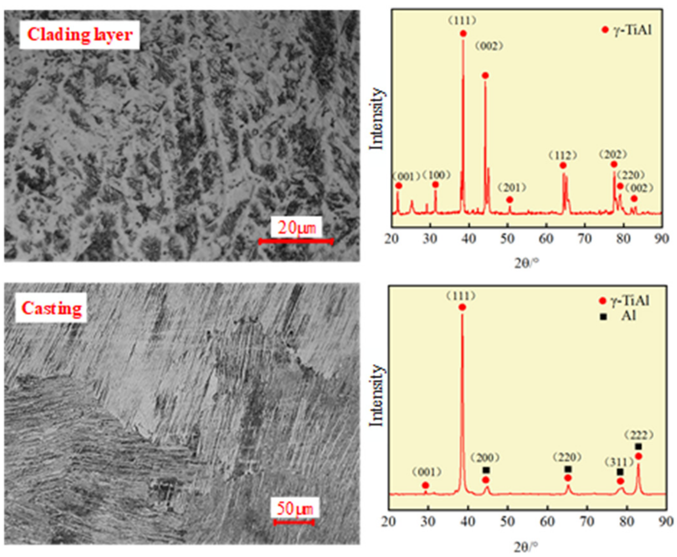

Figure 2. Metallographic Structure and Phase Composition of γ-TiAl Alloys

3.2. Analysis of Friction and Wear Properties

Figure 3 shows the friction coefficient curves of γ-TiAl castings and cladded parts under the conditions with and without ultrasonic vibration assistance. It is observed that, compared with the cladding layer, the friction coefficient curve of the casting is generally more stable. The reason for this phenomenon is that the formation of the cladding layer experiences rapid cooling and heating. During the solidification process of the material, the temperature gradient is relatively large. In the forming process, the overlapping area approximately undergoes a short-term heat treatment, resulting in inhomogeneity within the material structure and the easy generation of hard particles. In contrast, during the formation process of the casting, the temperature gradient is relatively small, and the internal structure is large and uniform, making the friction process relatively stable.

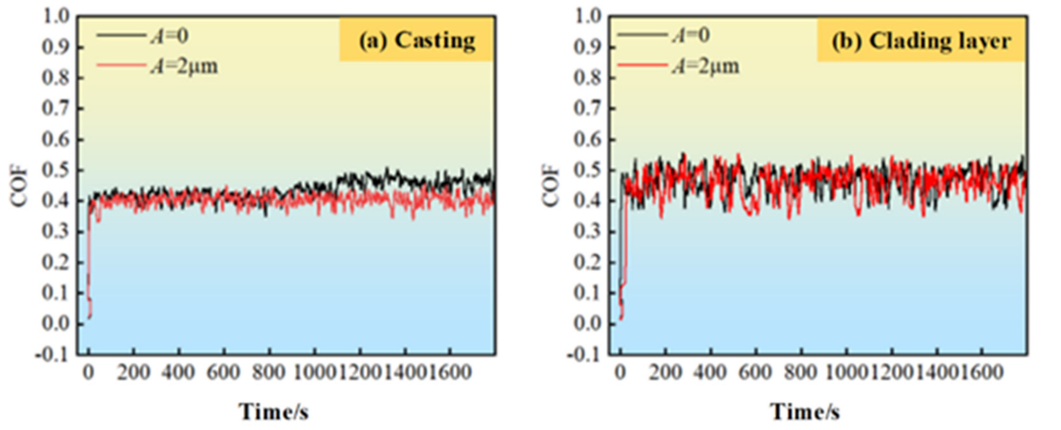

Figure 3. Surface Friction Coefficient of γ-TiAl Alloy

Figure 4 presents the average friction coefficients under different machining conditions. It is found that the friction coefficients of the surfaces of the casting and the cladded part processed by ultrasonic machining are smaller, which are decreased by 7.4% and 4.1% respectively compared with those of the surfaces processed by conventional machining. From a microscopic perspective, the microstructure of ultrasonic machining includes micro-scale protrusions and depressions. During the friction process, these microscopic protrusions and depressions reduce the actual contact area. According to the principles of tribology, when the actual contact area decreases, the frictional resistance decreases, thus reducing the friction coefficient.

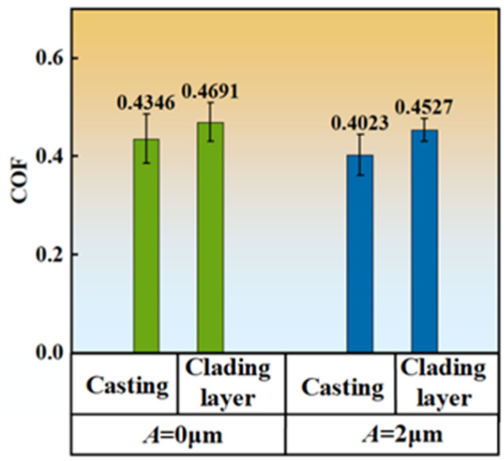

Figure 4. Average Friction Coefficient of γ-TiAl Alloy

Figure 5 depicts the macroscopic wear morphologies of surfaces under diverse machining parameters. The predominant wear mode is identified as material spalling. One contributing factor is that the γ-TiAl alloy exhibits high hardness yet low toughness. The sites of grain boundaries and phase boundaries within the material are susceptible to becoming stress - concentration regions. During the friction - and - wear experiment, the material endures cyclic loading. Consequently, fatigue cracks tend to initiate within the material, which are manifested as small - scale spalling.

A comparison of the surface wear conditions between the casting and the cladding layer reveals that the material spalling in the casting is more pronounced. As evident from Figure 2, the microstructure of the casting is coarser than that of the cladding layer. The relatively lower strength of grain boundaries in the casting renders grain - boundary slip and separation more likely to transpire. Additionally, the hardness and impact toughness of the casting are generally inferior to those of the cladding - layer material. The lower hardness and toughness render the surface of the casting more vulnerable to wear and fracture, thereby facilitating material spalling. In the case of the cladding - layer material, during the formation process, the molten pool adjacent to the air solidifies first, resulting in a relatively small grain size. In accordance with the Hall - Petch criterion, smaller grain sizes correspond to higher hardness values, thereby enhancing the wear - resistance property.

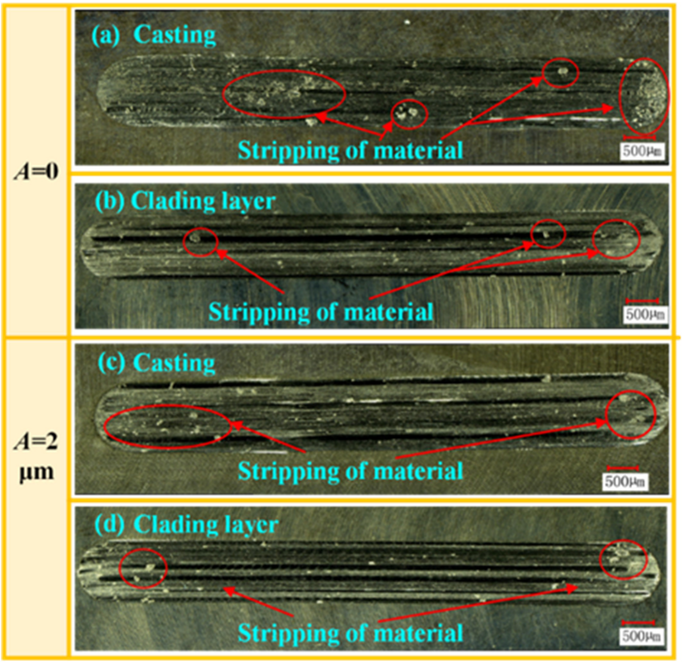

Figure 5. Macroscopic Wear Morphology of γ-TiAl Alloy

Figure 6 illustrates the three-dimensional wear morphologies of surfaces under different machining parameters. After observing the wear of the surfaces processed by conventional machining, it is found that there are numerous and uneven scratches at the bottom of the grooves. Moreover, there are curved edges at the bottom of the grooves of the casting. Combining with the analysis of the macroscopic wear morphology in Figure 5, it is likely that the uneven edges are caused by material spalling, indicating that the wear process of the surface processed by conventional machining is relatively unstable.

By comparing the wear cross-sectional areas, it is found that the cross-sectional areas of the cladded parts are all smaller than those of the castings. The wear cross-sectional areas of the surfaces processed by conventional milling and ultrasonic milling are reduced by 2.41% and 26% respectively, suggesting that the cladding layer has better wear resistance. The main reason is related to the fine-grain effect generated during the formation process of the cladding layer. The smaller microstructure improves the hardness and wear resistance of the material.

When comparing the worn surfaces of conventional machining and ultrasonic machining, it is evident that the cross - sectional area of the surface processed by conventional machining is larger. Specifically, the wear cross - sectional areas of the casting and the cladded part are increased by 19.26% and 57.27% respectively in the case of conventional machining. Besides the friction - reducing effect of the "fish - scale" morphology, it is likely that during the ultrasonic machining process, the high - frequency impact of the cutting tool on the material intensifies the work - hardening effect. This work - hardening effect increases the surface hardness, thereby enhancing the material's wear - resistance ability and reducing the wear area.

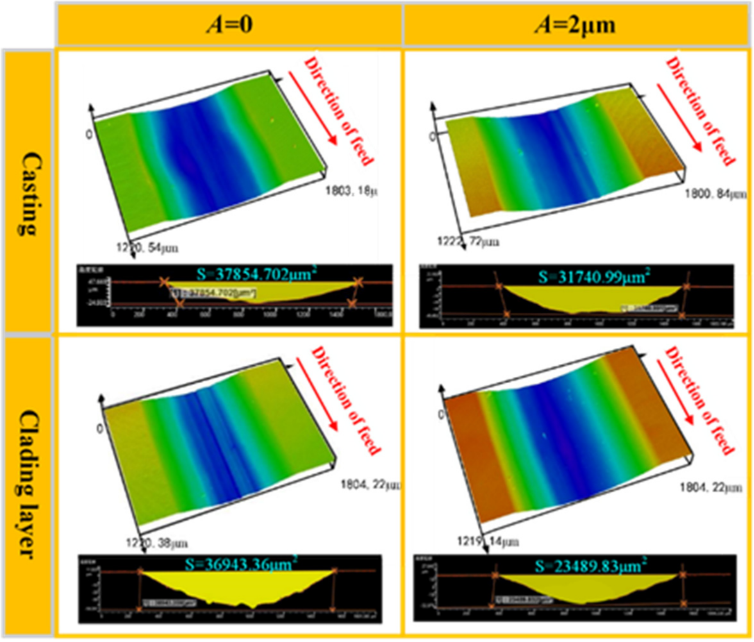

Figure 6. Three-dimensional Wear Morphology of the γ-TiAl Alloy

4. SUMMARY

Based on the characteristics of the internal microstructure of the material, the friction and wear properties of the γ - TiAl alloy under different machining parameters were compared, and the following conclusions were drawn.

(1) The internal microstructures of both the casting and the cladding layer are composed of lamellar structures. The cladding layer is composed of γ-TiAl lamellar structures, featuring relatively small sizes and uneven distribution, presenting a typical Widmanstätten structure. The metallographic structure of the casting is mainly composed of γ-TiAl phase lamellar structures and the incompletely fused pure Al phase, with larger and more uniform structures.

(2) By comparing the friction and wear properties of γ-TiAl castings and cladding layers, it has been found that due to the inhomogeneity of the internal structure of the cladding layer, the dynamic friction coefficient shows greater fluctuations, and the average friction coefficient is slightly larger than that of the casting. The main form of wear for both is material spalling. The wear cross-sectional area of the cladded part is smaller than that of the casting, which is reduced by 2.41% and 26% respectively under conventional milling and ultrasonic milling. Overall, the cladding layer exhibits more excellent friction and wear performance.

(3) By comparing the influence of ultrasonic vibration on the friction and wear properties, it is found that the friction coefficient of the surface processed by ultrasonic machining is smaller, which is reduced by 7.4% and 4.1% respectively compared with that of the surface processed by conventional machining. The wear cross-sectional area of the surface processed by ultrasonic machining is smaller than that of the surface processed by conventional machining, which is reduced by 19.26% and 57.27% respectively on the surfaces of the casting and the cladded part. The surface processed by ultrasonic machining has better wear resistance.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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