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Laser polishing of additive manufactured Ti alloys

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Abstract:

Laser-based additive manufacturing has attracted much attention as a promising 3D printing method for metallic components in recent years. However, surface roughness of additive manufactured components has been considered as a challenge to achieve high performance. In this work, we demonstrate the capability of fiber laser in polishing rough surface of additive manufactured Ti-based alloys as Ti-6Al-4V and TC11. Both as-received surface and laser-polished surfaces as well as cross-section subsurfaces were analyzed carefully by White-Light Interference, Confocal Microscope, Focus Ion Beam, Scanning Electron Microscopy, Energy Dispersive Spectrometer, and X-ray Diffraction. Results revealed that as-received Ti-based alloys with surface roughness more than 5 micron could be reduce to less than 1 micron through laser polishing process. Moreover, microstructure, microhardness and wear resistance of laser-polished zone was investigated in order to examine the thermal effect of laser polishing processing on the substrate of additive manufactured Ti alloys. This proof-of-concept process has the potential to effectively improve the surface roughness of additive manufactured metallic alloy by local polishing method without damage to the substrate.

Keywords: Laser polishing, additive manufacturing, Ti alloy, microhardness, wear resistance.

1. Introduction

Titanium (Ti) alloys have wide applications in aerospace and biomedical fields due to high specific strength and excellent corrosion resistance [1-3]. Conventional machinery manufacturing of titanium alloy components is very difficult caused by low thermal conductivity and high chemical reactivity with cutting tool materials [4-5]. Laser additive manufacturing (LAM) has attract much attention as a promising technology for producing titanium alloy parts using layer-by-layer manufacturing method [6-9]. LAM has been commonly used for fabricating or repairing large complex components including steam turbine blade, turbo-engine blade and turbo-engine case [10-12]. Surface roughness of LAM is usually higher than 10 μ m due to waviness of the scan tracks and layered structure [13-14].

Laser polishing has been considered as a potential method to reduce surface roughness of additive manufactured metals. It is mainly based on melting caused by thermal input of laser irradiation. When a laser beam of sufficient energy density impinges on material surface, morphological apexes reach the melting temperature and melt quickly. After molten pool is formed, liquid material tends to redistribute to the same horizontal level due to surface tension and gravity. When laser beam left, surface temperature of laser irradiated area will drop quickly, leading to molten pool solidified and surface roughness reduced correspondingly [15-17]. Compared with conventional mechanical polishing methods, laser polishing changes surface morphology by re-melting without altering or affecting bulk properties with high automation in environmental friendly way. In recent 20 years, laser polishing process has been developed for metallic materials, especially for difficult machining metals. For micro polishing with pulsed lasers, Chang *et al.* carried out surface polishing process of SKD61 tool steel using a microsecond fiber laser system, and reduced the surface roughness from 0.28 μm to 0.13 μm [18]. Guo *et al.* investigated polishing result of originally milled DF2 tool steel using microsecond Nd:YAG laser, which showed a decline of roughness value from 0.4 μm to 0.12 μm [19]. Giorleo *et al.* studied the a polishing process executed with a Nd:YVO4 laser radiation on Titanium sheet, and the surface was polished from 0.58 μm to 0.42 μm [20]. Different from micro polishing with pulsed lasers, laser macro polishing with high-power laser has also been developed to adapt much more complex surface. Bordatchev *et al.* contrasted the polishing effect of CW and pulsed lasers on Ni alloy, and reduced the surface roughness from 10 μm to 2 μm [21]. With the rise of LAM technology, laser polishing has been used to finish LAM parts surface. Lamikiz *et al.* investigated the polishing effect of high-power CW CO₂ laser on selective laser sintering (SLS) bronze alloy with roughness of 7.5 μm , and presented final surface roughness below 1.49 μm [22]. However, little literature is available in the public domain on laser polishing of additive manufactured Ti alloy components, especially for laser-based additive manufacturing method.

In this paper, we carry out laser polishing of two typical laser additive manufactured Ti alloys as TC4 and TC11 surfaces by nanosecond pulse laser. The aim of this study is to understand the effects of laser polishing on laser additive manufactured TC4 and TC11. By using scanning electron microscopy (SEM) and laser scanning confocal microscope (LSCM), we discuss how effective the laser treatment affects surface morphology and roughness of the titanium alloys, Vickers is used to investigate surface hardness, and a ball-on-flat wear tester is used to test wear resistance.

2. Experimental Procedures

2.1 Materials

Ti-6Al-4V (TC4) and Ti-6.5Al-3.5Mo-1.5Zr-0.3Si (TC11/BT9) titanium alloy blocks with a nominal composition were chosen, the alloy blocks was produced by laser additive manufacturing. Nominal composition of TC4 and TC11 titanium alloy are given in Table 1. Specimens were cut to thickness of 10mm for experiments by wire-electrode cutting.

Table 1 Actual chemical compositions of titanium alloys

Material	Al	V	Mo	Si	Zr	Fe	Ti
TC4	5.5-6.8	3.5-4.5	-	-	-	<0.30	Balance
TC11	5.8-7.0	-	2.8-3.8	0.20-0.35	0.8-2.0	<0.25	Balance

2.2 Laser processing

A nanosecond pulsed fiber laser (wavelength 1060 nm, pulse duration 220ns, repetition rate 500kHz, spot size 44 μ m) was used in this study to polish wire-electrode cutting surface of LAM Ti alloys. The optimized power density was 1.20×10^7 W/cm², and the optimized scanning speed was 200 mm/s. The irradiated area was 100 $\times$ 100 mm² in square using hatched scanning mode with 50% overlapping in the program. When laser was turned on, the specimen was placed under Ar gas protection.

2.3 Surface Characterization

Morphology was observed by FEI Quanta 450 FEG SEM with energy dispersive spectrometer (EDS) and Keyence VK-X series LSCM. Surface hardness was measured by FUTURE-TECH FM-800 Vickers, the loading force was chosen as 0.98N, and five indentation measurements were averaged for each microhardness. Holding time was 10s. Dry sliding friction tests were conducted using MFT-4000 multifunctional material surface performance tester. Al₂O₃ balls with a diameter of 5 mm were used as the counterpart. The applied load was 50 N with a linear velocity of 200mm/min and last for 30min. The wear tracks were measured by the Keyence LSCM.

3. Results and discussions

3.1 Effect of laser polishing on surface morphology

Laser polishing was demonstrated to be an effective polishing method for wire cutting machining surface of the two kinds of titanium alloys. After laser polishing, macro scale photographs of titanium alloys surface was shown in Fig. 1(a) and Fig. 2(a). As shown in Fig. 1(b) and Fig. 2(b), the rough as-received surfaces were well polished, laser melting tracks are observed on surface of titanium alloys. It indicates that during laser polishing process, morphological apexes of Ti alloys absorbed energy, reached the melting temperature in very short time. After surface material was melted, a fraction of the molten peak mass flowed into a valley driven by surface tension and gravity. When laser beam left, liquid material solidified with high cooling rate, leading to the peak-to-valley height reduced significantly. Laser scanning confocal microscope was employed to measure surface topography and surface roughness of laser polished titanium alloys. Fig. 1(c)-(d) and Fig. 2(c)-(d) show that after laser polishing, peak-to-valley height of TC4 surface decreased from 90 μ m to 4 μ m, and peak-to-valley

height of TC11 surface decreased from 80 μm to 4.5 μm . Average roughness (S_a) was also measured by laser scanning confocal microscope and calculated from the measured surface height data, as shown in Table 2, each of titanium alloys was effectively polished, surface roughness decreased from over 5 μm to less than 1 μm .

Fig.1 Effects of laser polishing on TC4 Ti alloy: (a) laser-polished region at the LAM surface; (b) SEM micrograph of the boundary between laser-polished region and as-received region; (c) Topographic image from LSCM of as-received surface; (d) Topographic image from LSCM of laser polished surface

Fig.2 Effects of laser polishing on TC11 titanium alloy: (a) laser-polished region at the LAM surface; (b) SEM micrograph of the edge of laser polished area; (c) Topographic image from LSCM of as-received surface; (d) Topographic image from LSCM of laser polished surface.

Table 2 Surface roughness of unpolished and polished surfaces

Material	As-received	Polished
TC4	5.226 μm	0.375 μm
TC11	7.21 μm	0.73 μm

3.2 Effect of laser polishing on microstructure

Microstructure in the surface layer and substrate of both TC4 and TC11 was investigated. Fig. 3(a)-(c) show typical microstructure of TC4 alloy substrate including needle shaped α phase (with lower V content) and β phase (with higher V content) after LAM processing [23-24], they also show the polished layer of TC4 with thickness of 170 μm , and acicular martensite α' can be observed in the polished zone. As shown in Table 3, chemical composition of main elements as Ti, Al, V in the melting zone is around 91.48%, 6.19% and 2.33%, which is in the range of α phase and β phase. The reason for the uniform elements distribution on the top of polished zone may be caused by the formation of martensitic α' phase after rapid melting and cooling during laser processing [25-26]. In agreement with microstructure analysis, XRD profiles in Fig. 3(d) indicate that as-received TC4 consists of α phase and β phase, while laser-polished surface mainly consists of α' martensitic phase without β phase. For $\alpha+\beta$ dual-phase Ti alloys, phase transformation $\alpha\rightarrow\beta$ takes place when temperature increases to the starting point of the transformation. When temperature increases up to β transus temperature (approximately 1273 K), $\alpha+\beta$ dual-phase completely transforms to be β phase. During cooling process when laser beam left, β phase would decompose to be whether secondary α or martensitic α' depending on cooling rates, and the critical cooling rate is around 410 K/s. If the cooling rate is higher than 410 K/s, β phase would transform to martensitic α' .

Cooling rate of pulsed laser irradiated molten metal surface could be very high, and previous works has demonstrated the relevant effect of pulsed laser on Mg alloy surface modification [27-28]. In this work, the cooling rates in the laser melted zone could be calculated from a one-dimensional thermal model by the product of temperature gradient. Time-dependent temperature gradient could be calculated from a governing equation for an adapted form of the usual time-dependent partial differential equation, the governing equation is as follows [29]:

$$\frac{\partial T(x, t)}{\partial t} = K \frac{d^2 T(x, t)}{dx^2} \quad (x > 0) \quad (1)$$

where K is the thermal diffusivity of the material and is equal to $k/\rho C_p$; k is the thermal conductivity of the materials; ρ is the density of the material and C_p is the specific heat. The initial condition of $T = T_0 = 298.15$ K was applied at time $t = 0$. For TC4 alloy, $k = 11.8$ W/m K, $\rho = 4.44$ g/cm³, $C_p = 703$ J/kg K. For TC11 alloy, $k = 17.2$ W/m K, $\rho = 4.48$ g/cm³, $C_p = 840$ J/kg K.

In thermal cycles of pulsed laser processing, the cooling rates of TC4 and TC11 were calculated 1.209×10^4 K/s and 9.238×10^3 K/s, which are much higher than 410 K/s. Under the rapid solidification and cooling rates, bcc β phase transforms completely into metastable hcp α' martensite phase by a diffusionless and shear-type transformation process. Therefore, after laser polishing, the

polished layers mainly consists of α' martensitic phase because of the phase transformation $\alpha+\beta\rightarrow\beta\rightarrow\alpha'$ [30-31].

Fig.3 Microstructure analysis of laser polished TC4 surface:

(a) Overview; (b) Microstructure of polished zone; (c) Microstructure of substrate; (d) XRD profiles.

Table 3 Chemical composition (wt. %) in positions of TC4 obtained from EDS analysis.

Elements	Ti	Al	V
α phase	92.58	6.93	0.49
β phase	90.16	5.99	3.85
Polished zone	91.48	6.19	2.33

Fig. 4(a)-(c) show typical microstructure of TC11 alloy including needle shaped α phase and β phase after LAM processing [32], it also shows the polished layer of laser polished TC11 with thickness of 90 μ m, and acicular martensite α' can be observed in the polished zone. As shown in Table 4, chemical composition of main elements is in the range of α phase and β phase. The reason for the uniform elements distribution on the top of polished zone may be caused by the formation of martensitic α' phase after rapid melting and cooling during laser processing. In agreement with microstructure analysis, XRD profiles in Fig. 4(d) indicate that as-received TC11 consists of α phase and β phase, while laser-polished surface mainly consists of α' martensitic phase without β phase.

Fig.4 Microstructure analysis of laser polished TC11 surface:

(a) Overview; (b) Microstructure of polished zone; (c) Microstructure of substrate; (d) XRD profiles.

Table 4 Chemical composition (wt. %) in positions of TC11 obtained from EDS analysis.

Elements	Ti	Al	Mo	Zr	Si
α phase	83.92	7.88	5.04	2.75	0.41
β phase	89.12	5.58	3.89	1.29	0.12
Polished zone	88.74	5.71	3.55	1.73	0.27

3.3 Effect of laser polishing on surface mechanical properties

The microhardness distributions of titanium alloys after laser polishing is shown in Fig. 5. It can be seen that the average hardness of initial substrates of TC4 and TC11 is about 345HV and 400HV, respectively. In laser polished layer, the hardness increases by 32% and 42% than that of the initial material due to the formation of α' martensitic phase on surfaces. The reason is, α' martensitic has a hexagonal closed-packed (hcp) structure, and β phase has a body-centred cubic (bcc) structure. As hcp structure has higher bulk modulus value than bcc structure, polished layer becomes harder than as-received surface [33].

Fig.5 Microhardness distributions in laser polished surface: (a) TC4; (b) TC11.

Fig. 6 shows a cross section profile of wear track of titanium alloys before and after laser polishing. The figure shows that the wear tracks of the laser polished surfaces are smaller than those of as-received surfaces. Wear rate is used to evaluate the wear resistant of the samples, and it is defined as:

$$W = \Delta V / (L * D) \quad (2)$$

where ΔV is the volume of the wear trace, D is the sliding distance and L is the applied load in the experiment [34]. Fig. 7 shows wear rates of titanium alloys before and after laser polishing, it can be seen that the wear rates of the laser polished TC4 and TC11 are higher than the wear rates of respective as-received materials. The increase of wear resistance in the polished zone a can be ascribed to the formation of hard α' martensitic phase after laser polishing.

Fig.6 Cross section profile of wear tracks of titanium alloys before and after laser polishing:
(a) TC4; (b) TC11.

Fig.7 Wear rate of titanium alloys before and after laser polishing:
(a) TC4; (b) TC11.

4. Conclusions

Surface analysis of LAM TC4 and TC11 after laser polishing was carefully examined. The main experimental findings and analyses of this study may be summarized as follows:

1. As-received surfaces produced by wire-electrode cutting had been effectively polished, surface roughness decreased from over $5\mu\text{m}$ to less than $1\mu\text{m}$.
2. For both TC4 and TC11, after laser polishing, the polished layers mainly consists of α' martensitic phase formed by rapid melting and cooling after laser polishing, which is different than the $\alpha+\beta$ dual-phase microstructure in the substrate.
3. Due to the formation of α' martensitic in the polished region, surface microhardness of TC4 and TC11 increases about 32% and 42% than that of as-received surface, respectively.
4. Wear resistance of laser polished TC4 and TC11 surfaces are largely enhanced, compared to that of as-received surface.

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