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Influence of energy fluence and overlapping rate of femtosecond laser on surface roughness of Ti-6Al-4V

Yong Yang,[a,b,c] Rui Lou,[a,b] Xu Chen,[a] Wenhui Fan,[a,d,*] Jing Bai,[a] Weiwei Cao,[a] Guanghua Cheng,[a,*] and Jinhai Si[b]
[a]Chinese Academy of Sciences, Xi'an Institute of Optics and Precision Mechanics, State key Laboratory of Transient Optics and Photonics, Xi'an, China
[b]Xi'an Jiaotong University, School of Electronics and Information Engineering, Key Laboratory for Physical Electronics and Devices of the Ministry of Education and Shaanxi Key Lab of Information Photonic Technique, Xi'an, China
[c]University of Chinese Academy of Sciences, Beijing, China
[d]Shanxi University, Collaborative Innovation Center of Extreme Optics, Taiyuan, China

Abstract. The Ti-6Al-4V polished by femtosecond laser processing is first investigated. The surface nanoparticles of Ti-6Al-4V induced by femtosecond laser have been characterized by scanning electron microscopy and energy dispersive spectrometry, and the influence of laser fluence and the overlapping rate of laser beam on surface roughness have also been analyzed. Moreover, the relationship between the laser parameters and the surface roughness of Ti-6Al-4V has been revealed, and the fine surface roughness of Ti-6Al-4V is obtained based on the optimized femtosecond laser processing parameters. [DOI: 10.1117/1.OE.58.10.106107]

Keywords: femtosecond laser; surface roughness; nanoparticles; Ti-6Al-4V.

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1 Introduction

Ti-6Al-4V, also called TC4, is an alpha–beta titanium alloy with high specific strength, low weight ratio, and excellent corrosion resistance, having wide applications in the biomechanical and aerospace industries.[1] In particular, the surface roughness of TC4 plays a critical role in metallic dental implants and affects the accumulation of plaque,[2] and it also determines the performance of functional components in aerospace applications.[3] Moreover, other applications involving surface roughness include reduced frictional heating in moving parts, increased surface area for chemical etching, and improved fluid flow for biofluidic applications.[4,5] Therefore, achieving fine surface roughness on the selected region of TC4 is an extremely important challenge that needs to be overcome.

Compared to conventional mechanical polishing, laser polishing can offer an acceptable solution on the microscale, especially if selective surface micropolishing is utilized. Laser polishing usually falls into three categories: continuous (or quasi-continuous) wave laser polishing, short-pulse laser polishing, and ultrashort-pulse laser polishing. Pfefferkorn et al.[6] performed two-pass polishing using a microsecond laser to improve the TC4 surface finish, where a surface roughness ranging from 172 to 86 nm was achieved in the first pass and was further improved to 47 nm in the second pass. Ma et al.[7] polished TC4 components using a nanosecond fiber laser, and the surface roughness achieved was ~1 μm. Bhaduri et al.[8] determined that for TC4 polishing using nanosecond and millisecond lasers in air, it is very difficult to eliminate the recast layer and microcrack, which originate from the surface and thermal effects owing to the long-pulse laser polishing.

On the contrary, femtosecond laser processing is one of the efficient methods to overcome this problem, owing to the shorter pulse duration. The unique advantages of femtosecond laser, including high peak power and high accuracy of ablation on metal targets, have been utilized widely. Recently, Taylor et al.[9] investigated experimentally the effectiveness of femtosecond lasers as alternative laser sources for noncrystalline silicon and germanium polishing. They found that both the laser pulse energy and the overlapping rate of the laser beam influence the surface roughness in femtosecond laser polishing; in addition, the mechanisms for femtosecond laser polishing of nonmetals have been investigated. However, to the best of our knowledge, this is the first study analyzing the surface roughness of TC4 processed using a femtosecond laser.

In this study, the influence of energy fluence and overlapping rate on the surface roughness of TC4 polished using a femtosecond laser was investigated experimentally. The results showed that the surface roughness of TC4 varied with the energy density and overlapping rate of the femtosecond laser. The optimized polishing parameters were obtained by comparing the experimental results. There was no microcrack observed on the TC4 surface polished by using the femtosecond laser, and the surface chemical composition of TC4 was nearly consistent. Statistical analysis results regarding the size distribution of TC4 nanoparticles agreed well with the theory of Samuels;[10] this theory states that mechanical polishing is the resultant of filling and cutting. On the other hand, the mechanism for producing nanoparticles using a femtosecond laser is distinct. This involves four mechanisms: laser ablation, laser fragmentation, laser melting (LM), and laser heat effect.

2 Experimental Setup

The experimental setup used for polishing a flat TC4 surface is shown in Fig. 1, including a galvanometer scanner, three-dimensional translation stage, and femtosecond laser.

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*Address all correspondence to Wenhui Fan, E-mail: fanwh@opt.ac.cn; Guanghua Cheng, E-mail: gcheng@opt.ac.cn

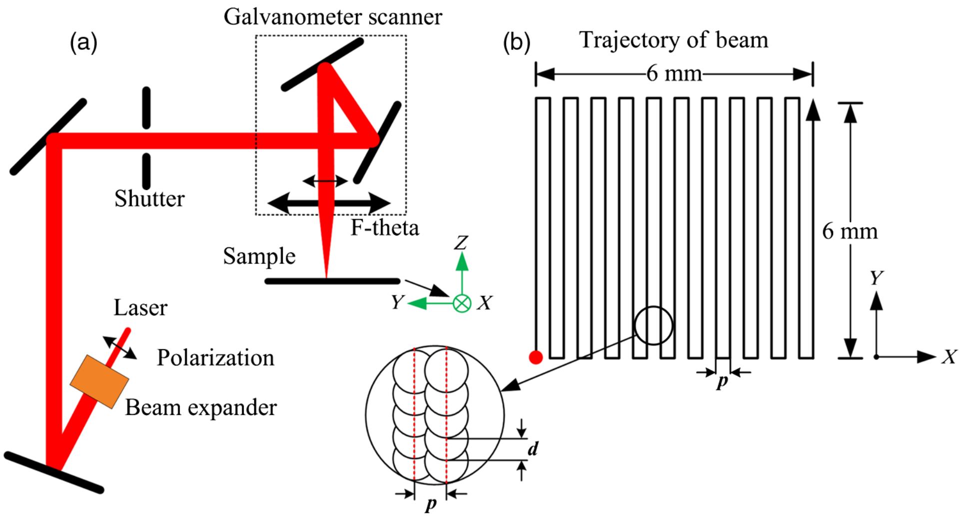


Fig. 1 (a) Schematic representation of the experimental setup used in femtosecond laser polishing. (b) Schematic representation showing the zigzag path of the laser beam. The circular inset is the magnification of the path followed by laser pulses.

Gaussian-profile femtosecond laser beams operating at a repetition rate of 100 kHz and pulse duration of 224 fs with a central wavelength of 515 nm were generated by a Yb:KGW laser system (Pharos, LIGHT conversion).

The energy of the incident laser beam was varied using a high-voltage polarizer. The incident laser beam was perpendicular to the TC4 sample, mounted on a computer-controlled three-dimensional translation stage. The scan trajectories of femtosecond laser polishing were set by adjusting the translation stage and galvanometer optical scanner via a time sequence controller. The TC4 sample used was a standard TC4 sheet, which was obtained after hot-rolling and acid-washing processes. The surface roughness of TC4 sample after hot-rolling and pickling is about 1.656 μm.

The asperities of the laser-induced surface were measured using a stylus profiler (KLA-Tencor P7) with a 2-μm-radius tip and 60-deg angle. The diameter of the laser-induced nanoparticle and surface morphology was determined using a ZEISS SPRA 55 field-emission scanning electron microscope (SEM) operated in the secondary electron imaging mode. The chemical compositions of the nanoparticles and polishing area were characterized using an energy dispersive spectrometer (EDS).

The overlapping rates of the Y (determined by the scanning speed and pulse frequency) and X axes (determined by the step-over direction) were calculated by using Eqs. (1) and (2),[11] respectively:

$$\Lambda = \left(1 - \frac{v/f}{D + v\tau}\right) \times 100, \tag{1}$$

$$\Delta = \left(1 - \frac{p}{D}\right) \times 100, \tag{2}$$

where v is the beam scanning speed along Y axis (constant, 20 mm/s); f is the laser repetition rate, depending on the overlapping rate (varied from 1 to 100 kHz); D is laser spot diameter at the focal plane (29 μm, measured with a beam profiler); τ is the pulse duration(s); and p is the step size.

If $p = 21.8$ μm, the overlapping rate of the Y axis, Λ, is identical to that of the X axis, Δ. The same value was set to consider the effect of energy overlapping of the laser beam along both directions.

3 Results and Discussion

The influence of the laser fluence and overlapping rate of the femtosecond laser on the TC4 surface roughness was analyzed. The analysis process was divided into three parts. In the first two parts, the influence of the laser fluence and overlapping rate on surface roughness was analyzed, and the optimized laser parameters were determined. In the third part, the optimized laser parameters were utilized to polish the TC4 surface. The surface roughness, chemical composition, and microstructure of the polishing area were analyzed.

3.1 *Influence of Femtosecond Laser Fluence*

Figure 2 represents the variation of surface roughness (ΔRa) and mean diameter of the nanoparticles on the TC4 surface polished using different laser fluences (32.8, 74.4, and 109.4 $\mathrm{J/cm^2}$). Triangular points on the solid line indicate the variation of surface roughness, and rectangular points on the dashed line represent the mean diameter of the nanoparticles on the TC4 surface. Points marked "A" and "B" and the ellipses on the lines correspond to insets (a) and (b), respectively. One of them depicts the variation of surface roughness (ΔRa), which is shown in inset (a), the other depicts the size distribution of nanoparticles, which is shown in inset (b). The mean diameters of the nanoparticles on the TC4 surface were determined from the size distribution. All experimental data were normalized considering the inclinations and concave pits on the TC4 surface.

Figure 3 illustrates surface morphologies of the TC4 nanoparticles during ablation under different laser fluences with a single laser shot. There are dark and bright nanoparticles in the images, owing to the signals with different intensities and different angles in the SEM instrument. The nanoparticles on the TC4 surface are almost spherical.

Figure 4 shows a comparison of the elemental composition on the TC4 surface. It can be seen that the chemical

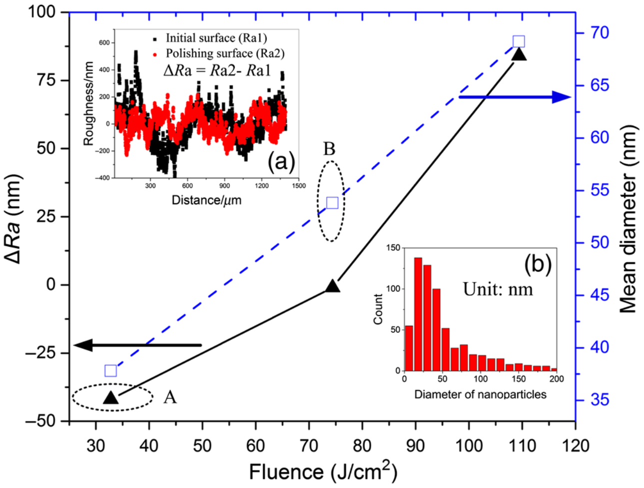


Fig. 2 Points on the solid lines depicting the variation of surface roughness on laser fluence. Points on the dashed line indicate the mean diameter of nanoparticles on the TC4 surface. Inset (a) shows the variation of surface roughness at point A and inset (b) presents the size distribution of nanoparticles at point B.

elements have little change after the TC4 surface was polished using the different laser fluences. The carbon on the sample surface could be because of surface contamination caused by organic material before the polishing process. On the other hand, oxygen was found on the sample surface after laser polishing, which could be generated from air during the polishing process. The rest of the composition on the sample surface remained unchanged.

The experimental results clearly show that size of nanoparticles induced by the femtosecond laser depends on the laser fluence. The stronger the laser fluence utilized, the higher the variation of surface roughness is. Because small nanoparticles were effective in improving the surface roughness of the TC4 sample, a better surface was obtained with the smaller nanoparticles ablated using low laser fluence. So, it is obvious that ΔRa will decrease when the size of the nanoparticles induced by femtosecond laser polishing gets smaller. Moreover, the main chemical elements on the TC4 surface after femtosecond laser polishing remained almost unchangeable.

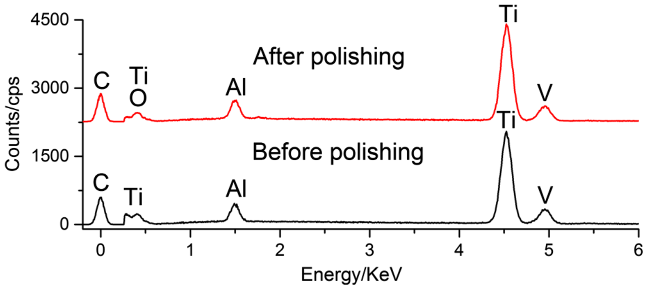


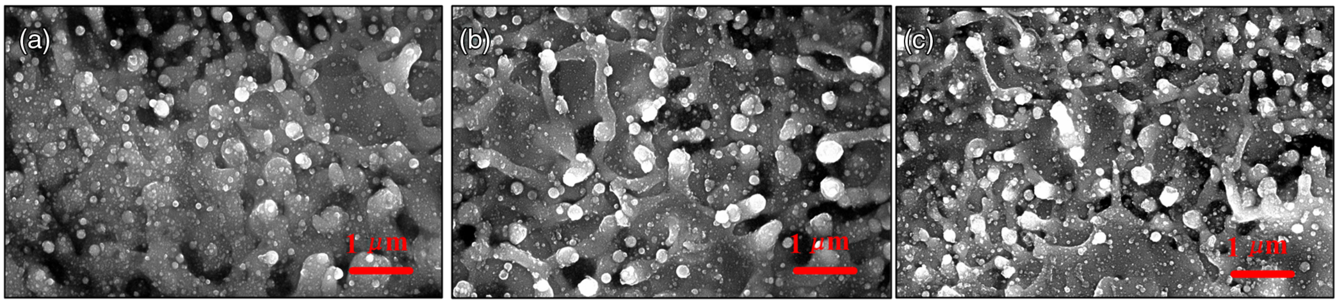
Fig. 4 EDS spectra of the sample before and after polishing.

Our results show that laser polishing involves filling and fine-cutting. The depressions on the TC4 surface could be filled by the nanoparticles induced by the femtosecond laser, and the peaks on the TC4 surface could be cut away by femtosecond laser. Femtosecond polishing is different in approach but equally satisfactory in result with mechanical polishing, where the polishing mechanism is the resultant of filling adjoining depressions and fine cutting by the abrasive particles.[10] Further, the statistical analysis results regarding nanoparticles further confirm the findings of many works, which state that nanoparticles induced by laser are large when laser fluence is strong.[12–14] The research in this part first combines the theory of conventional mechanical polishing with femtosecond-laser-ablated nanoparticles mechanism, and also it happens to hold the same view with femtosecond laser polishing. Moreover, we established the relationship between femtosecond laser fluence and TC4 surface roughness.

3.2 *Influence of Femtosecond Laser Overlapping Rate*

Figure 5 shows the dependence of the surface roughness on the TC4 surface as function of the beam overlapping rate. Five overlapping rates at a laser fluence of 74.4 $\mathrm{J/cm^2}$ were selected, and (I), (II), and (III) are the laser ablation regions with different trends in terms of the surface roughness on the TC4 surface after femtosecond laser polishing. The three images represent the characteristic morphology of regions (I), (II), and (III) respectively. The dotted line corresponding to $\Delta Ra = 0$ in the horizontal direction represents the original surface before laser polishing.

In region (I), the greater the overlapping rate of the laser beam, the smaller is the size of the nanoparticles. The overlapping rate of the laser beam produces small nanoparticles because femtosecond laser fragmentation can produce smaller nanoparticles.[12,15,16] In region (II), particle aggregation is obvious when the laser beam overlapping rate



E = 109.4 J/cm² **E = 74.4 J/cm²** **E = 32.8 J/cm²**

Fig. 3 SEM images of TC4 surface subjected to single laser shot with laser fluences at (a) 109.4, (b) 74.4, and (c) 32.8 $\mathrm{J/cm^2}$.

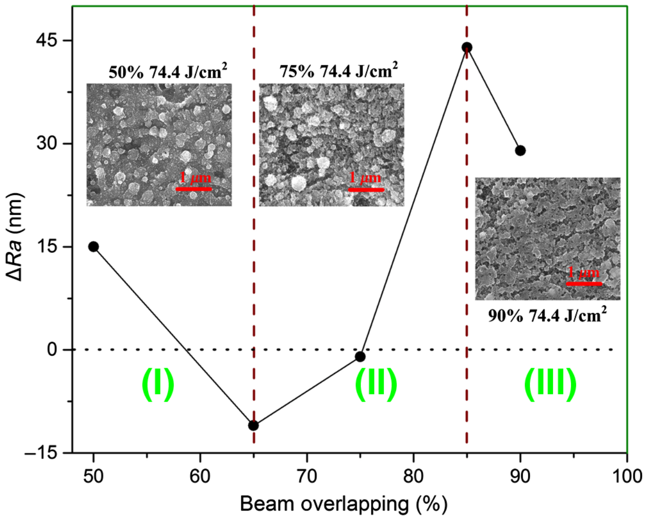


Fig. 5 Surface roughness as a function of beam overlapping rate (50%, 65%, 75%, 85%, and 90%). (I), (II), and (III) are the laser polishing regions with different trends in roughness variation. Insets reveal the surface morphologies resulting from using different overlapping rates.

increases, owing to the transition of mechanism of nanoparticle formation.[17–19] LM plays a leading role in this region, resulting in rising up of line and larger nanoparticles. In region (III), with the overlapping rate increasing, the reduction in surface roughness is obvious, due to agglomerate formation irradiated by femtosecond laser, and becomes even more apparently at high overlapping rate.[20] Thus, a fine surface can be attained by the certain overlapping rate and fluence of femtosecond laser, as reported in some studies on silicon.[21,22]

The analysis above has sought to find out the inner relation under different overlapping rate of femtosecond laser polishing. In every region, there are obvious different mechanisms. The femtosecond laser ablated and fragmented on surface of TC4 to produce small nanoparticles in region (I). Mechanism of producing nanoparticles changes into LM in region (II). And there is the heat effect at a high overlapping rate beam shined in region (III). Therefore, the influence of femtosecond laser overlapping rate depends on the mechanism of femtosecond-laser-induced nanoparticles, and the interaction between femtosecond laser and TC4 surface is very complicated.

Table 1 Actual chemical compositions of TC4 surface polished by femtosecond laser.

Item	Ti	C	O	Al	V
Before polishing	83.36	9.08	0	5.11	2.45
After polishing	84.78	3.85	3.66	5.34	2.37

3.3 *Fine TC4 Surface after Femtosecond Laser Polishing*

In Fig. 6, the surface roughness (1.381 μm) of TC4 after femtosecond laser polishing is 16.6% better than that of the original surface (1.656 μm). Moreover, the SEM image depicts the surface morphology, showing many nanoparticles. However, there is no microcrack observed on the polishing area. Moreover, in Table 1, the actual chemical compositions before and after femtosecond laser polishing are presented, which are consistent with the EDS spectra in Fig. 4.

Compared to nanosecond, millisecond, and continuous lasers, the surface polished by femtosecond laser not only has good surface roughness but also has much less defects, such as recast layer and microcracks. The microcracks generated by laser polishing mainly come from the thermal stress, and it is very challenge to eliminate the microcracks on TC4 surface polished by long-duration laser.[8,23] However, it is hard to generate microcracks and recast layer by femtosecond laser polishing, due to the weak thermal stress and residual stress on TC4 surface.[24]

Although the mechanism of less surface defects observed on TC4 surface polished by femtosecond laser is still not quite clear, some relevant factors, such as laser duration, temporal shaping, and spatial shaping, have been discussed and analyzed.[25,26] Among them, laser duration is very important one. When TC4 surface is polished by femtosecond laser,

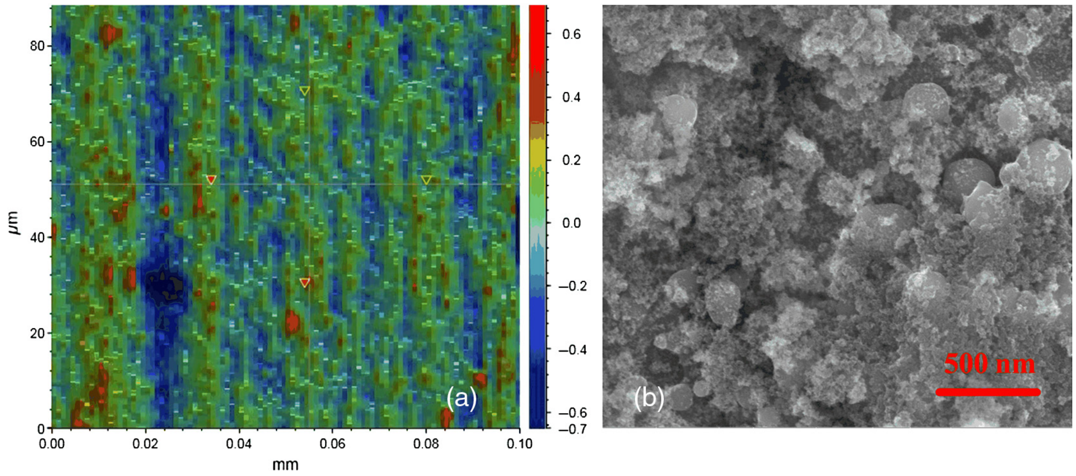


Fig. 6 (a) Improved surface roughness (1.381 μm) of TC4 after femtosecond laser polishing. (b) Microstructure of TC4 surface after femtosecond laser polishing.

the heat or other form of energy do not dissipate efficiently out of the beam spot because the laser pulse duration is much shorter than the thermal diffusivity time across the absorption depth, which is about 10^{-11} s.[27] In other words, there is no enough time to transmit energy via vibrations of crystal lattice during femtosecond laser polishing. The main mechanism of femtosecond laser processing is Coulomb explosion, although it sometime appears very weak and very limited melting under the condition of high laser fluence or high laser repetition frequency.[28–30]

In a word, compared to other laser polishing with longer pulse durations, TC4 surface polished by femtosecond laser can obtain good surface without obvious microcrack and recast layer.

4 Conclusions

In summary, the TC4 surface polished by femtosecond laser was analyzed. The laser fluence and overlapping rate of the femtosecond laser have a major influence on the surface roughness of TC4. First, the stronger the laser fluence, the greater is the variation of surface roughness. Second, the influence of the overlapping rate of the femtosecond laser on surface roughness of TC4 is very interesting. Different overlapping rates correspond to a different mechanism of TC4 nanoparticles formation during femtosecond laser polishing. At low laser overlapping rates, small nanoparticles were induced by laser ablation and laser fragmentation. As for high laser overlapping rates, large nanoparticles were generated from small nanoparticles by LM. If the laser overlapping rates further increased, the heat effect becomes seriously. Our study was the first of its kind, investigating the relationship between the mechanism of nanoparticles formation by femtosecond laser and its polishing parameters; a high-quality TC4 surface without microcracks was experimentally obtained via femtosecond laser polishing.

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Yong Yang is an assistant professor at the State Key Laboratory of Transient Optics and Photonics, Chinese Academy of Sciences. His current research interests include application of ultrafast laser processing, development of ultrafast laser processing equipment, ultrafast laser-inducing materials surface and its application.

Biographies of the other authors are not available.