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ORIGINAL ARTICLE

Surface integrity of titanium part by ultrasonic magnetic abrasive finishing

K. Zhou[1] **· Y. Chen**[1] **· Z. W. Du**[1] **· F. L. Niu**[1]

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Abstract The surface integrity of titanium part is poor after milling; it is unable to meet the accuracy requirements for use. To solve this problem, the ultrasonic vibration-assisted magnetic abrasive finishing was proposed to be used for the surface finishing treatment. The finishing experimental result shows that the efficiency of ultrasonic magnetic abrasive finishing is 40 % higher than magnetic abrasive finishing. The milling texture on part surface faded or disappeared after ultrasonic magnetic abrasive finishing. The surface original micro-cracks have been completely removed. The surface stress state changed from the residual tensile stress 280 MPa before finishing to residual compressive stress 20 MPa after finishing. It verified that the ultrasonic magnetic abrasive finishing can efficiently promote the surface integrity of titanium parts and ultimately gain the best surface quality and performance.

Keywords Magnetic abrasive finishing · Machining efficiency · Ultrasonic vibration · Surface integrity

1 Introduction

With the rapid development of new technology machinery industry, the mechanical parts are facing the increasing demand for material performance. Because of the excellent physical and chemical properties, titanium material has been widely used in the aerospace industry, shipbuilding industry, automotive manufacturing, and many other fields [1]. But its superior performance also brings enormous difficulties to accurate machining. The titanium parts are usually formed by the five-axis CNC milling machine. Their surface will residual a large number of milling textures and micro-cracks due to the effect of squeezing from milling cutter, which seriously affects the stable operation of the parts in the mechanical system [2, 3]. To improve the performance and service life of titanium parts, accuracy machining needs to be done to the parts surface before use. The traditional grinding processes mostly belong to the rigid contact; they are easy to generate a lot of grinding heat and burn the part surface, and high accuracy machining trajectory is demanded for them [4, 5]. To finish this kind of special material parts, in the study of Yang-Zhi et al., the electrochemical process was applied to the surface finishing. The machining efficiency and accuracy are high [6]. But the process machining uniformity is effected by a variety of factors, and the machining result is instable. Even worse, it may pollute the environment; however, Yang Shen et al. used the electric discharge machining to manufacture the titanium alloy parts. Compared with the electrochemical way, this method can also gain a high machining quality [7]. But the machining efficiency is low relatively, and the process could easily lead to the surface internal stress increasing and part deformation; the machining dimensional accuracy is poor; it greatly affects the use of the part [8].

As a new finishing technology, magnetic abrasive finishing is using the magnetic abrasive particles as the cutting tool,

✉ K. Zhou
zk521life@163.com

[1] Institute of Advanced Grinding Technology, University of Science and Technology, Liaoning, Anshan, China

which will aggregate along the magnetic lines to form a magnetic abrasive particle brush (referred to magnetic abrasive brush) with certain stiffness in the magnetic field. When the magnetic pole rotates relative to the part, the magnetic abrasive brush will rotate together with the magnetic pole to complete the part surface finishing precisely [9, 10]. As the cutting tool of magnetic abrasive finishing, the magnetic abrasive particle usually contains two components; they are ferromagnetic particle and abrasive particle [11]. The ferromagnetic particle makes the magnetic abrasive particles have excellent magnetic properties; when magnetized, the magnetic abrasive particles will be gathered into a magnetic abrasive brush under the magnetic force. The abrasive particle makes the magnetic abrasive particles have super high hardness; it will ensure the magnetic abrasive particles with continuous micro-cutting to high hardness material parts [12, 13]. The composition of magnetic abrasive brush makes it have characteristics like flexibility, self-sharpening, self-adaptive characteristics, and so on [14]. It can realize finishing the inner surface of space pipes, free-form surface parts, and any other tiny parts which the traditional processes are difficult to finish or cannot finish. During the machining process, not only it won't produce residual stresses but also the textures and surface micro-cracks were uniformly eliminated with the removal of the milling layer. The residual stress was released, and the surface performance was improved significantly. In actual finishing process, the defect of low efficiency in magnetic abrasive finishing can be eliminated assisted by frequency ultrasonic vibration and achieve the consequent of finishing the titanium parts with high efficiency and high quality [15–17].

2 The principle of ultrasonic magnetic abrasive finishing

As shown in Fig. 1, it is the mechanism of ultrasonic magnetic abrasive finishing process. The entire machining device is mainly composed of two parts: they are ultrasonic vibration part and magnetic abrasive finishing part. The main parts of the ultrasonic vibration include the ultrasonic generator, the piezoelectric transducer, the slip ring, and the horn. The upper end portion is connected to the machine spindle so that a high-speed rotation is delivered to the ultrasonic device. At the same time, it can generate a high-frequency vibration along the axial direction [18]. The magnetic abrasive finishing part includes an axial magnetic pole and the magnetic abrasive particles; the magnetic pole is fixed at the front portion of the ultrasonic device. Adjust the gap between the magnetic pole and the part surface to 1–2 mm; then, the magnetic abrasive particles were filled into the machining gap uniformly to form a magnetic abrasive brush [12]. When the machine tool and the ultrasonic device started up, the magnetic abrasive brush would complete a composite motion included high-speed rotation and high-frequency vibration at the same time. This composite motion was applied to the part surface directly. Finally, it could realize finishing the part surface perfectly and efficiently [19].

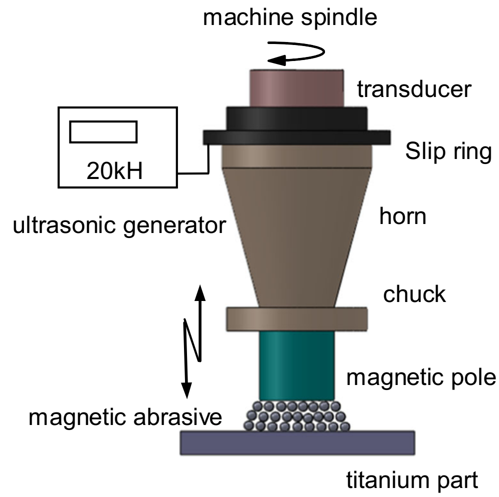

Fig. 1 Principle of ultrasonic magnetic abrasive finishing

From the analysis of carried force and movement state to a single magnetic abrasive particle in Fig. 2, the magnetic abrasive particle is subjected to the joint action of magnetic force F_y along the magnetic line and the magnetic force F_x perpendicular to the magnetic line. The synthesis of the magnetic forces F_x and F_y is magnetic force F, which advances the magnetic abrasive particles pressing into the part surface with a sufficient rigidity and drawing out with the rotation of the magnet pole, reaching the purpose of micro removing and finishing the part surface [20]. The

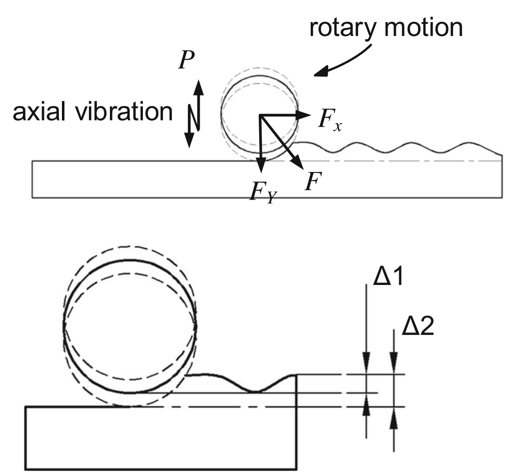

Fig. 2 The force and movement analysis of single particle by ultrasound magnetic abrasive finishing

relationship between the friction removal and the finishing pressure can be represented by the Princeton Equation as follows:

$$R(x,y) = kP(x,y)V(x,y) \quad (1)$$

where $R(x, y)$ is the material removal amount per unit time; $P(x, y)$ is the instantaneous finishing pressure; $V(x, y)$ is the magnetic pole rotation.

From Eq. (1), the material removal amount per unit time $R(x, y)$ is proportional to the finishing pressure $P(x, y)$ when the magnetic pole rotation speed $V(x, y)$ and the other factors are homogeneous. When machining by the magnetic abrasive finishing process, the finishing pressure is only provided by the magnetic force F. For the magnetic strength is limited, the finishing pressure P_F provided by the magnetic force is limited too. If the part surface hardness is relatively large, the finishing pressure P_F provided by the magnetic force could not press the magnetic abrasive particles into the part surface, so the finishing process may not be completed, and the finishing efficiency will decrease at last [21–24]. When the ultrasonic vibration is introduced, the finishing pressure working on part surface from the magnetic abrasive brush includes the instantaneous pulse pressure P_0 generated by the high-frequency ultrasonic vibration in addition to the magnetic force F. So the material removal rate $R(x, y)$ by the ultrasonic magnetic abrasive finishing can be expressed as Eq. (2):

$$R(x,y) = k(P_F + P_0)V(x,y) \quad (2)$$

As shown in Fig. 2, Δ1 is the cutting depth for the magnetic abrasive finishing, and Δ2 is the cutting depth for the ultrasonic magnetic abrasive finishing. Comparing and analyzing the two cutting depths show that the cutting depth from magnetic abrasive particles is significantly increased after introducing the ultrasonic vibration. Because the instantaneous pulse pressure P_0 increased, the number and depth of the magnetic abrasive particles pressed into the part surface. Thus, it increased the material removal rate of the part surface. The magnetic abrasive brush attracted by the magnetic pole can make a high-speed rotation. The rotation advanced the magnetic abrasive particles rolling, turning, striking, and extruding frequently on the part surface. It still maintained the magnetic abrasive brush's self-sharpening to produce a sustained finishing effect [17, 25].

3 Experiment procedures

In order to verify the feasibility in improving the surface integrity of titanium parts by ultrasonic magnetic abrasive finishing, the finishing experiment to titanium parts has been done. The original part surface roughness, the surface morphology, the surface micro-cracks, the sectional microstructure and the residual stress were measured as the initial data after milling. Figure 3 shows the ultrasonic magnetic abrasive finishing experimental device. First of all, the titanium part was positioned and fixed on the workbench. The ultrasonic magnetic abrasive finishing device was connected to the machine spindle. Then, the magnetic pole was fixed to the ultrasonic device and the machining gap between the magnetic pole and the part surface was adjusted to 1–2 mm. The magnetic abrasive particles and grinding fluid were uniformly mixed and added to the machining gap. Then, the ultrasonic frequency and the rotation speed of the machine spindle were set up [26, 27]. Under the premise that the magnetic abrasive particles cannot be thrown out, the higher the speed is the better the finishing effects are.

The part finished in this experiment is a titanium planar part; the used magnetic pole is made of strong magnetic material Nd-Fe-B to get the highest magnetic force [28, 29]. The magnetic abrasive particles is the fused aluminum oxide magnetic abrasive. It is made from the ferromagnetic phase (iron) and the abrasive phase (alumina or silicon carbide) by processes of mixing, compacting, drying, sintering, crushing, screening, and so on [11]. The used grinding fluid is the Labor En SR-9911 grinding oil. The parameters shown in Table 1 could get the highest efficiency during magnetic abrasive finishing [30].

The part from the workbench when it reached the specified finishing time was removed, cleaned, and dried. The surface roughness was measured by the surface roughness tester; the surface morphology was observed by the 3D optical microscope; the part surface sectional microstructure changes were observed by the metallographic microscope; the surface residual stress was measured with X-ray diffraction. At last, the initial data with the measured experimental data after 30 min finishing were compared and analyzed.

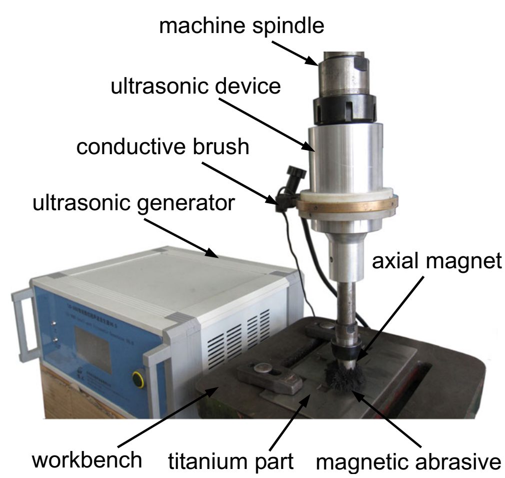

Fig. 3 Ultrasonic magnetic abrasive finishing experimental device

Table 1 The experimental conditions

Name	Parameters
Part	Titanium part
Spindle speed	1200 r/min
Ultrasonic frequency	16 KHz
Magnetic abrasive particle	Corundum magnetic abrasive (350 μm) 10 g
Magnetic pole	Φ10×10 mm
Grinding fluid	Oil-based fluid 5 ml
Machining gap	1–2 mm
Finishing time	30 min
Finishing area	2500 mm^2

4 Experimental results and discussion

4.1 Change of surface texture

The original surface morphology, the surface morphology after 30 min magnetic abrasive finishing and the surface morphology after 30 min ultrasonic magnetic abrasive finishing were measured, respectively, by the 3D optical microscope, then compared them. The surface morphologies are shown in Fig. 4:

During the milling process with the part, there exists the actions like pressing, friction, cutting, and so on between the milling tool and the part surface. Accompanied with a slight vibration from the machine, it will lead to the temperature rise and deformation on the surface layer [31]. Multiple milling paths result from the milling process superimposed on each other; it would lead to visible duplicate and regular deformations. The deformations displayed on the part surface were the machining texture. As shown in Fig. 4a, a large amount of scaly projections can be seen produced on the surface after milling process. These scaly projections superposed to form many regular peaks and troughs. The overall state performed to be the machining texture, and the part surface quality was poor. From Fig. 4b, with the cusp effect of magnetic abrasive finishing, the surface projections would be prior removed so that the height difference between the peaks and troughs in milling texture was reduced. From this figure, the surface quality by magnetic abrasive finishing has been significantly improved compared with the quality before finishing. However, due to the regular machining trajectory during the finishing process, there would produce regular helix processing texture, and the surface quality was still not good enough. As shown in Fig. 4c, it is found that the part surface milling textures have been all removed compared with Fig. 4b. The surface quality is more dense and uniform by ultrasonic magnetic abrasive finishing.

Compared with the magnetic abrasive finishing, the ultrasonic magnetic abrasive finishing pressure includes not only the magnetic force but also the frequency pulse pressure generated from the axial ultrasonic vibration. The magnetic abrasive particles did the horizontal cutting motion and the impact extrusion motion vertical to the part surface at the same time. When the magnetic abrasive particle was located on the milling peak, the particle would be pressed into the peak under the axial instantaneous ultrasonic vibrations and impact action. And the process increased the contacting time between particles and the peak surface relative to the magnetic abrasive finishing, so that the material removal amount on both sides of each peak was nearly equal, and always maintained a class-symmetric circular curve [27]. The surface morphology is more uniform and the material removal rate is also higher.

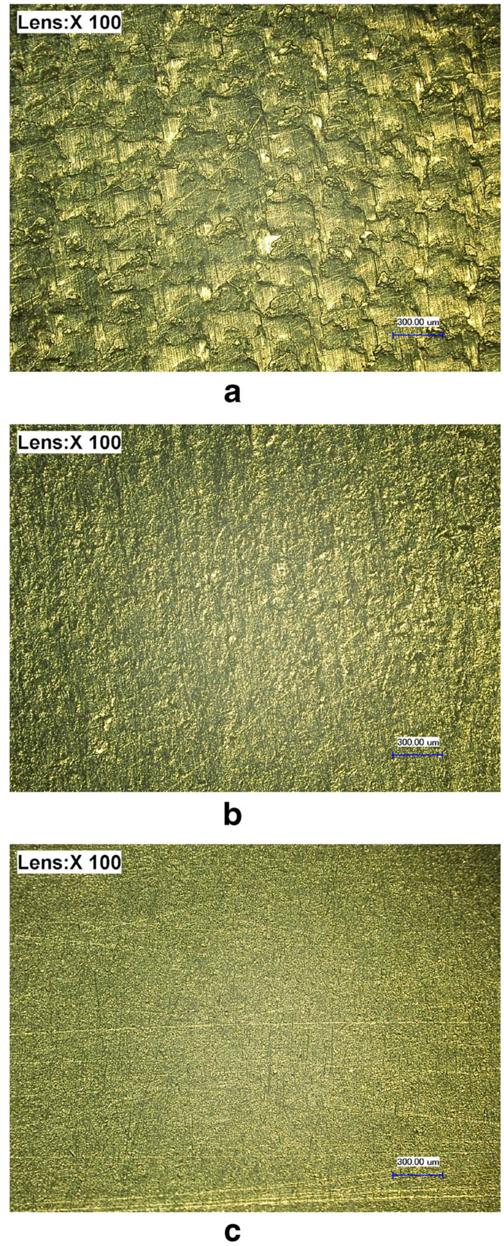

Fig. 4 Titanium part surface morphology at the magnification ×100. **a** The original surface morphology. **b** The surface morphology by magnetic abrasive finishing. **c** The surface morphology by ultrasonic magnetic abrasive finishing

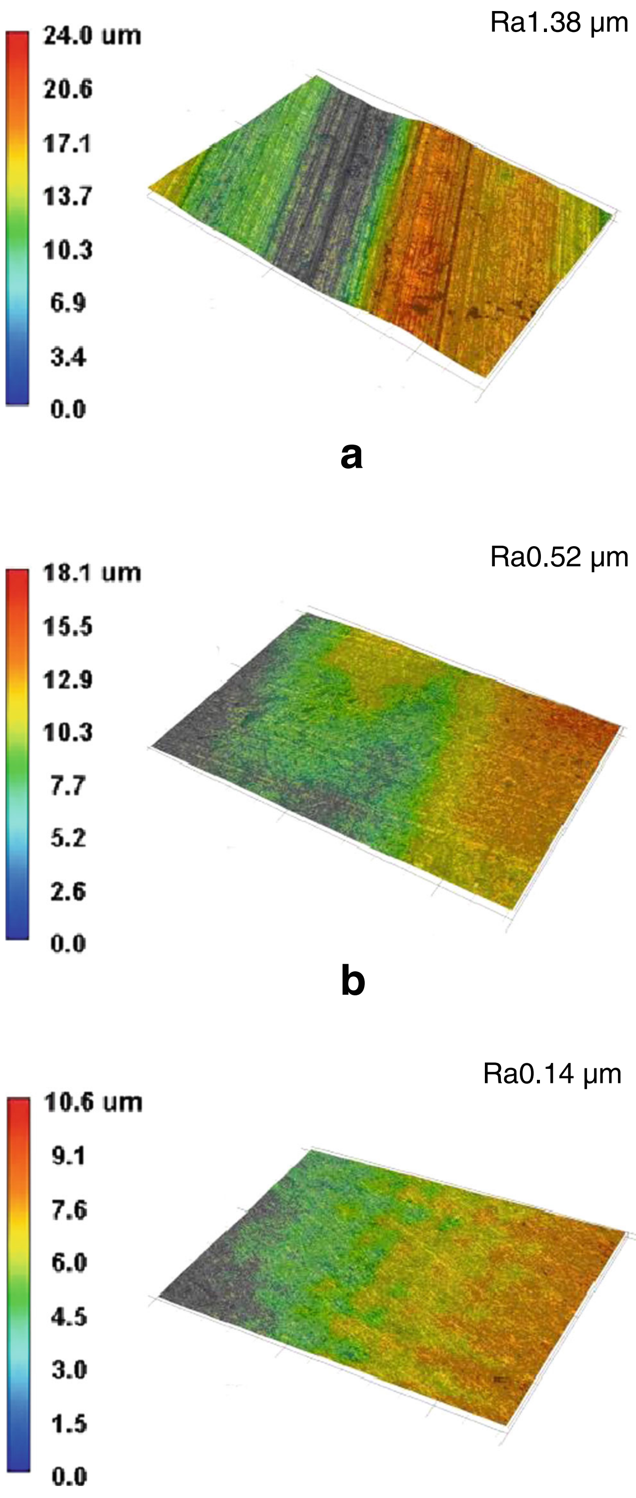

Fig. 5 Titanium part surface morphology at the magnification ×100. **a** The original surface morphology. **b** The surface morphology by magnetic abrasive finishing. **c** The surface morphology by ultrasonic magnetic abrasive finishing

From Fig. 5, the original part surface is uneven. After 30 min finishing time, the part surface has been finished well by ultrasonic magnetic abrasive finishing; the surface became flat and smooth. The magnetic abrasive finishing can also make the part surface better relative to the original surface quality. However, it is not better than the ultrasonic magnetic abrasive finishing. The surface textures have not been removed completely, some light textures are still can be seen somewhere on the surface. The surface morphology is not uniform after 30 min magnetic abrasive finishing compared with the surface quality by ultrasonic magnetic abrasive finishing.

In addition, the machine vibration may lead to discontinuity on surface during milling and cause a sudden squeeze pressure increases in local area to form micro-cracks. As shown in Fig. 6a, the micro-cracks can be found produced in local area of part surface after milling. If put it into use without any finishing process, it is easy to result in the crack propagation and the part's early fracture finally. Figure 6b shows that the part surface micro-cracks disappeared after ultrasonic magnetic abrasive finishing. Moreover, the pits were also removed effectively which were produced by crack and squeeze. The milling textures and surface micro-cracks' removal can effectively improve the fatigue strength of the part and extend the useful time of it.

As an important part of the surface integrity study, the surface roughness is also an important indicator of the quantitative characterization to microscopic surface irregularities. The milling textures generated during the machining process and the uneven generated from adhesion with tearing between the tool and part can seriously affect the part surface roughness [2]. If the surface roughness is too large, the part may cause local crack prematurely or fracture during use. It may shorten the life of the part seriously [32]. As shown in Fig. 7, the surface roughness change before and after finishing. The diagram cannot only show the surface roughness but also can clearly observe the part surface bump change. Concluding from the measurement, the part surface roughness fell from Ra1.38 μm to Ra0.14 μm effectively by the ultrasonic magnetic abrasive finishing; it decreased a lot. In addition, from Fig. 7a, the original texture can be seen clearly on part surface before finishing; the surface roughness Ra curve fluctuates heavily. Compared with Fig. 7a, the Ra curve fluctuation of the magnetic abrasive finishing in Fig. 7b is discovered weak. The average amplitude has decreased, but there are still obvious peaks and valleys on surface. Comparing Fig. 7b with c, the surface roughness Ra curve fluctuations have been found greatly weaken by ultrasonic magnetic abrasive finishing. The part surface machining texture becomes lighter, and the finishing quality of the part surface is higher.

The different surface roughness between magnetic abrasive finishing and ultrasonic magnetic abrasive finishing is due to the different finishing pressure during processing. The surface roughness in Fig. 7b is reduced only by the grinding action in horizontal direction. The finishing pressure is small, and the

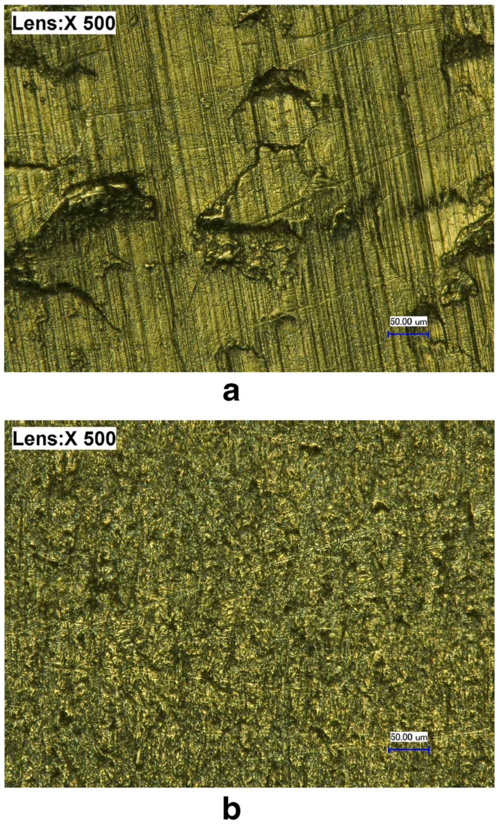

Fig. 6 Titanium part surface micro-cracks at the magnification ×500. **a** The original surface micro-cracks. **b** The surface micro-cracks by ultrasonic magnetic abrasive finishing

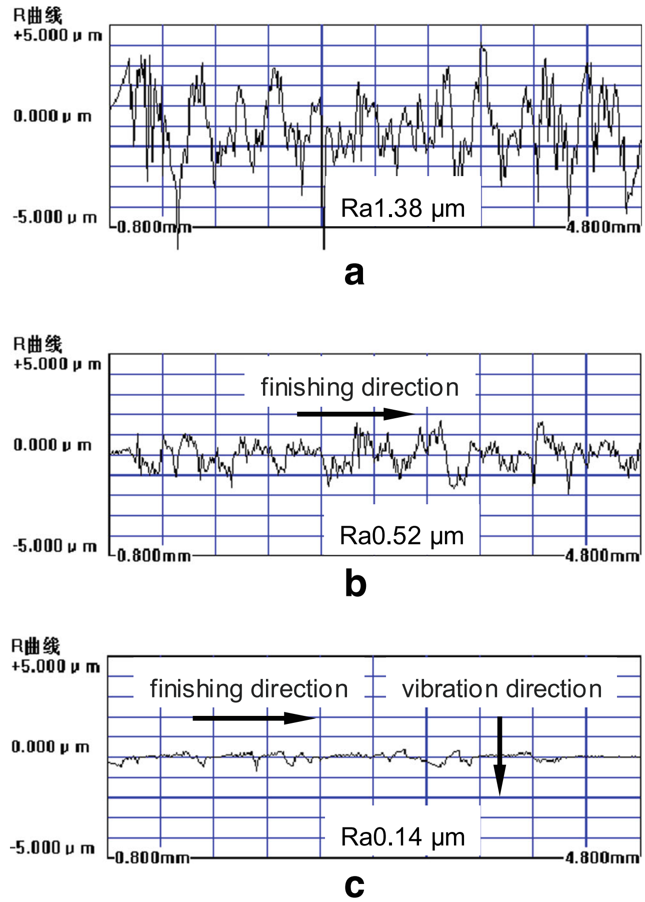

Fig. 7 Titanium part surface roughness Ra changes before and after ultrasonic magnetic abrasive finishing. **a** The original surface roughness. **b** The surface roughness by magnetic abrasive finishing. **c** The surface roughness by ultrasonic magnetic abrasive finishing

finishing efficiency is low. In Fig. 7c, the machining work contains not only the grinding action in horizontal direction but also the high-frequency vibration in vertical direction. The finishing pressure was increased rapidly, and the finishing efficiency was improved. When the part is finished by the two processing methods, the finishing pressure between the machining gap was detected with dynamometer. The average pressure of magnetic abrasive finishing pressure is 0.25 N, and the average pressure of ultrasonic magnetic abrasive finishing process is 0.36 N. The surface roughness measurements were taken with the change of the finishing time. As shown in Fig. 8 are the change states by two methods.

As we can see from the picture, the ultrasonic magnetic abrasive finishing efficiency is significantly higher, and the finishing quality is slightly better than magnetic abrasive finishing. Calculating the slope value of the surface roughness lines, it appears that the ultrasonic magnetic abrasive finishing efficiency is 40 % higher than the magnetic abrasive finishing without any assisting technique [27].

4.2 Change of surface crystal structure

From Fig. 9, comparing the cross-sectional microstructure of the part surface before and after finishing, it can be seen that the shape and volume of microscopic lattice in the part near surface layer is uneven and blurred in Fig. 9a. Compared with the part substrate, the lattice structure in surface layer is very

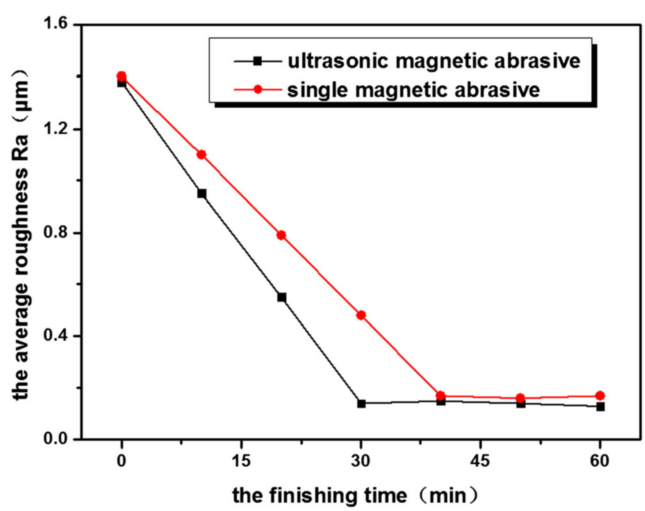

Fig. 8 Change in titanium part surface roughness with finishing time by different process

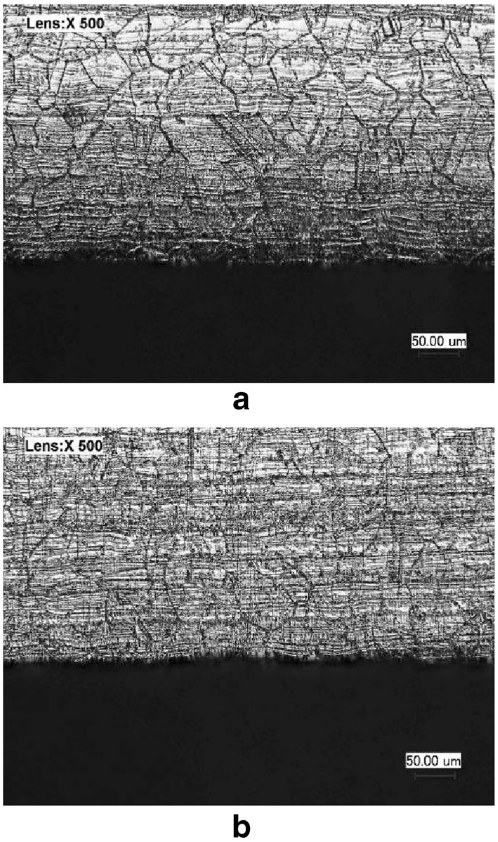

Fig. 9 Titanium part sectional microstructure by ultrasonic magnetic abrasive finishing. **a** The original surface sectional microstructure. **b** The surface sectional microstructure by ultrasonic magnetic abrasive finishing

different. This is because the titanium part is machined by CNC milling machine, the milling surface suffered from severe extrusion, friction, and heat. The part's surface lattice would be stretched, twisted and broken because of compression and slippage. As a result, the part surface generated a metamorphic layer that was different from the substrate material. The metamorphic layer covered the titanium substrate so that the material performance would not be reflected well [33]. Figure 9b shows the microscopic organizational structure change of the part surface by ultrasonic magnetic finishing. The contrast shows the crystal structure in part surface layer, and the matrix crystal structure is almost identical after ultrasonic magnetic abrasive finishing. First of all, the ultrasonic magnetic abrasive finishing belongs to the micro-cutting processes; it does not produce excessive squeeze between the tool and the part surface; so, the finishing process will not produce too much heat. The crystal structure of the part surface layer will not change as finishing process carries on [9, 19]; secondly, during the ultrasound magnetic abrasive finishing process, for the part's cladding material was grinded out, the crystal structure metamorphic layer produced by the milling action got shallow or disappeared consequently. The surface layer crystal structure similar or identical to the part substrate is exposed [27]. This milling effect restored the excellent physical and chemical properties of titanium alloy material; thus, the overall performance of the part can be improved.

4.3 Change of residual stress

Due to the rigidity contact between the part and the tool during milling, the extrusion and friction generated by the tool will produce a large amount of residual tensile stress on the part surface, and the part's fatigue life will be greatly shorten [34, 35]. The surface stress states were tested with the X-ray interferometer after milling. They are the surface stress state after magnetic abrasive finishing and the surface stress state after ultrasonic magnetic abrasive finishing. θ change from 0 to 30° continuously during the measurement by adjusting the X-ray incidence angle θ continuously was made; then, nine detection curves from experimental data were selected, and the refraction angle size of $2\theta_{\Psi}$ was recorded.

According to Eq. (3), the residual stress measurement is calculated in Table 2;

$$\sigma = -\frac{E}{2(1+\mu)}\cot\theta_0 \frac{\pi}{180}\frac{\partial\left(2\theta_{\psi}\right)}{\partial\left(\sin^2\psi\right)} \tag{3}$$

where E is the material elastic modulus; μ is the material poison's ratio.

Table 2 shows that the stress state on part surface is residual tensile stress after milling. The stress size is 280 MPa. The magnetic abrasive finishing process belongs to micro cutting; the cutting force is smaller in the process and it won't produce new residual stress. After the magnetic abrasive finishing, the magnetic abrasive particles introduced compressive stresses which extruding on the surface by the action of magnetic force, the surface milling texture was effectively removed. So, the surface roughness was also greatly improved, the tensile residual stress of the part surface was significantly reduced, and the ultrasonic vibration introduction made the magnetic abrasive particles strike the surface frequently. The surface layer metal produced times of slight plastic deformation to produce a shot peening layer in the surface finally, so the surface stress state got further changed. It could be detected by the X-ray interferometer that the residual stress in the part surface have changed from the original tensile stress to

Table 2 Residual stress calculations

Residual stress	After milling	Magnetic abrasive	Ultrasonic magnetic abrasive
σ(MPa)	+280	+40	−20

compressive stress; the stress value size was 20 MPa. The experiments show that the process of ultrasonic magnetic abrasive finishing can help improve the overall fatigue life of titanium parts.

5 Conclusions

In this study, base on the magnetic abrasive finishing, the ultrasonic is proposed to increase the magnetic abrasive finishing efficiency and the surface integrity to titanium parts. The finishing experiment to titanium parts was done, and the data of surface to verify the finishing quality was measured. The flowing conclusions were drawn:

1. Ultrasonic magnetic abrasive finishing process introduces the ultrasonic vibration based on the flexible machining of original magnetic abrasive finishing, not only can play magnetic abrasive finishing's characteristic of flexible, self-sharpening, adaptive, micro-cutting, small cutting forces, and any other advantages but also with ultrasonic vibration to effectively improve the processing efficiency and quality of magnetic abrasive finishing.
2. After finished by ultrasonic magnetic abrasive finishing process, the titanium parts surface texture and the micro-cracks are removed evidently; the part surface topography is uniform and fine. The part surface roughness is effectively reduced from Ra1.38 μm to Ra0.14 μm; the surface quality has been significantly improved.
3. With the ultrasonic magnetic abrasive finishing, the part surface material could be micro-removed, the surface lattice structure deterioration generated by the milling force will also be reduced or eliminated, and the part surface material and the substrate material tend to be consistent. It is conducive to promote the performance of the titanium alloy.
4. With the ultrasonic magnetic abrasive finishing, the surface stress state changed from the original milling tensile stress 280 MPa to compressive residual stress 20 MPa; the part's fatigue strength and useful time can be effectively improved.

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