Technological Rule of Ultrasonic Assisted Magnetic Abrasive Finishing of Titanium Alloy

T Y Jiang, F J Ma*, X Liu, Y Liu, S F Zhang and Z H Sha
School of Mechanical Engineering, Dalian Jiaotong University, No. 794, Huanghe Road, Shahekou District, Dalian 116028, China

*The corresponding author’s e-mail address: mafj@djtu.edu.cn

Abstract. The influence of machining time, ultrasonic amplitude, spindle speed and machining gap on surface roughness and material removal rate were studied and analysed through the experiment of UAMAF of titanium alloy. The results show that the surface roughness decreases rapidly in the beginning and then gradually stabilizes as the machining time increases. The surface roughness reduces from the original Ra0.94μm to Ra0.10μm, when the machining time reaches 30min that is optimum machining time. The material removal rate drops approximately linearly with the increase of machining time. The surface roughness decreases significantly and the material removal rate increases rapidly as the ultrasonic amplitude rises. The surface roughness reduces to Ra0.12μm and the material removal rate increases to 30.5mg/h, when the ultrasonic amplitude is up to 14μm. The surface roughness decreases in the beginning and then increases, and the material removal rate rises in the beginning and then falls, as the spindle speed increases. The surface roughness achieves a minimum of Ra0.11μm and the material removal rate reaches a maximum of 22.74mg/h, when the spindle speed is 1400r/min. The surface roughness drops in the beginning and then rises, and the material removal rate increases in the beginning and then decreases, as the machining gap enlarges. The optimum machining gap is about 1.25mm. In this case, the surface roughness achieves a minimum of Ra0.16μm, and the material removal rate reaches a maximum of 17.7mg/h.

1. Introduction
Titanium alloy with high strength, high temperature resistance, corrosion resistance, good fatigue properties and fracture toughness has been widely used in key parts of aviation, aerospace, shipping and energy fields [1]. Extremely high requirements for finishing quality and efficiency are required in precise finishing of titanium alloy parts. However, titanium alloy is typical difficult-to-machine material because of its small elastic modulus, high viscosity and poor process performance. Therefore, the quality and efficiency in finishing of titanium alloy have yet to be improved.

For achieving high-quality and high-efficiency finishing, a variety of finishing technologies that compounds with multiple energies have been applied to the finishing of difficult-to-machine materials such as titanium alloy, aluminium alloy and superalloy. Ultrasonic assisted magnetic abrasive finishing (UAMAF) can significantly improve the finishing quality and efficiency of difficult-to-machine materials among these technologies through the organic compounding of ordinary magnetic abrasive finishing and ultrasonic vibration [2-3]. The finishing principle of UAMAF is shown in Figure 1. Ultrasonic vibration is applied on magnetic pole to make magnetic abrasive impact workpiece surface...
at a velocity of $V_u$ with a high-frequency, on the basis of rotating at a speed of $V_s$. The action of magnetic abrasive on workpiece is high-frequency and high-speed impacting besides cutting. The amount of magnetic abrasives in contact with the surface of workpiece per unit time is increased. Finally, high-quality and high-efficiency finishing of difficult-to-machine materials is achieved [4]. Therefore, many researches on UAMAF have been carried out by many scholars.

![Figure 1. Finishing principle of UAMAF.](image)

Y P Lu et al. [5] proposed to attach ultrasonic vibration to magnetic abrasive finishing. It is revealed that enhancing the cutting ability of the abrasive brush is critical to improve the efficiency of magnetic abrasive finishing by analysing mathematical removal model of traditional magnetic abrasive finishing. J Ma et al. [6] used the self-developed UAMAF setup to carry out single factor test on the finishing of 45# steel. The influence of magnetic induction on the quality of finishing was analysed. Surface roughness reduces significantly as magnetic induction increases. The surface roughness decreases from the original Ra1.35μm to Ra0.11μm, when the magnetic induction is 0.9T. The experiment of UAMAF of the inner wall of TA18 titanium alloy tube was carried out by Y Tan et al. The results show that the surface roughness of TA18 tube reduces from the original Ra1.2μm to Ra0.07μm after finishing for 50min with the vibration frequency of 19kHz and the amplitude of 10μm [7]. H Yun et al. conducted UAMAF test on Al$_2$O$_3$ ceramic tubes. It is found that the increase of vibration frequency and spindle speed can improve the material removal rate of UAMAF and reduce the surface roughness. The optimum surface roughness is Ra0.03μm, and the maximum material removal rate is 48.5mg/h after finishing for 50min with the vibration frequency of 19kHz. The surface roughness decreases to Ra0.03μm, and the material removal rate increases by 17.5mg/h, when the spindle speed increases from 600r/min to 2000r/min [8]. The comparative test of ordinary magnetic abrasive finishing and UAMAF of AISI52100 hardened steel with hardness HRC61 was conducted by R Mulik et al. The results show that the finishing quality of UAMAF is significantly improved, and the surface roughness can be as low as Ra0.022μm [9-10]. UAMAF has advantages in achieving high-quality and high-efficiency finishing as shown in above studies. But relatively few studies on the influence of machining parameters on surface roughness and material removal rate in UAMAF of difficult-to-machine alloys such as titanium alloy and superalloy were researched. Therefore, more and more comprehensive and in-depth studies on UAMAF of titanium alloy are necessary to be carried out.

A systematic technological test of UAMAF of titanium alloy is conducted in this study. Surface roughness and material removal rate of UAMAF of titanium alloy materials under different finishing parameters are measured by surface roughness meter, ultra-depth 3D microscope and precision analysis scale. The effects of machining time, ultrasonic vibration and other finishing parameters on UAMAF are studied and analysed.
2. Experiment setup and conditions

The test of UAMAF is carried out on the experiment setup as shown in Figure 2. It is built by the ultrasonic vibration system integrated on a three-axis CNC machine tool. The resonant frequency of ultrasonic vibration system is 21.91kHz and the amplitude is continuously adjustable between 5μm and 15μm. The magnetic pole is NdFeB magnet of type N38 with the diameter of 6mm and the length of 75mm. The coolant is Castrol 9930 water soluble cutting fluid with a concentration of 8%. The abrasive is iron-based diamond magnetic abrasive with the average particle diameter of 300μm prepared by chemical composite plating. Its surface topography is shown in Figure 3. The other finishing parameters used in the test are shown in Table 1.

![Experiment setup of UAMAF.](image)

![Surface topography of magnetic abrasive.](image)

| Finishing parameters       | value  |
|---------------------------|--------|
| Spindle speed (r•min⁻¹)    | 1000   |
| Feed rate (mm•min⁻¹)       | 20     |
| Machining gap (mm)         | 1.25   |
| Finishing time (min)       | 20     |
| Finishing length (mm)      | 10     |
| Amplitude (μm)             | 10     |
| Ultrasonic frequency(kHz)  | 21.91  |

The workpiece material is TC4 titanium alloy in the test of UAMAF. The initial surface of the workpiece is obtained by milling. The milling parameters are that the spindle speed is 2500r/min, tool diameter 20mm, feed per tooth 0.05mm and cutting depth 0.1mm. The coolant is water-based lubricating cutting fluid. The surface roughness after milling is about Ra0.94μm.

The average value of three measurements that are detected by Talysurf PGi840 Surface Roughness Profiler before and after finishing is taken as the surface roughness of the workpiece.
The material removal amount of finishing is measured by Sartorius CP225D precision analytical balance. The workpiece before and after finishing needs to be cleaned with an ultrasonic cleaner for 20 minutes and dried with electric thermostatic drying oven for 15min at 150°C. The material removal rate is calculated by

$$Q = \frac{M_1 - M_2}{t}$$  \hspace{1cm} (1)

where \(M_1\) is the weight of the workpiece before finishing(mg); \(M_2\) is the weight of the workpiece after finishing(mg); \(t\) is the machining time(h).

3. Results and discussion

3.1. Effect of machining time on surface roughness and material removal rate

The machining time in the test is 10min, 20min, 30min, 40min and 50min respectively and the other finishing parameters are shown in Table 1. Single factor test for UAMAF is conducted. The effect of machining time on surface roughness and material removal rate is shown in Figure 4.

![Figure 4. Effect of machining time on surface roughness and material removal rate.](image)

It can be seen from Figure 4 that the surface roughness decreases as the machining time increases. The surface roughness declines from the original Ra0.94μm to Ra0.10μm, after finishing for 30min. But the surface roughness of workpiece is decreasing more and more slowly as the machining time goes further. The surface roughness reduces from Ra0.10μm to Ra0.08μm only, after finishing for another 20min.

The reason for this phenomenon is that UAMAF has vertex effect. Original surface of workpiece is obtained by milling. The difference of height between peak and valley of surface is comparatively large, and the magnetic abrasive has a higher pressure on the peak. Therefore, workpiece will be removed more quickly at the peak, resulting in a faster decrease in surface roughness. In addition, high-frequency and high-acceleration impact of ultrasonic vibration causes the magnetic abrasive to perform ultrasonic shot peening while performing cutting removal. Plastic flow is produced from the wave peak of workpiece surface to flow into the valley and fill it. However, the difference of height between peak and valley becomes smaller, and the vertex effect is weakened as the finishing progresses. The entire plane begins to be finished by the magnetic abrasive, when the groove between adjacent peaks can be machined, after finishing for a certain period of time. Therefore, the surface roughness decreases more and more slowly.

It also can be seen from Figure 4 that the material removal rate drops approximately linearly with the increase of machining time. The material removal rate is 10.5 mg/h at 50 min, which is 55% lower than that of 10 min. The reason for this result is that some diamond grains on magnetic abrasives are worn or fall off as the machining time increases, and the machining performance of magnetic abrasives is reduced. As a result, the material removal rate decreases approximately linearly.
3.2. Effect of ultrasonic amplitude on surface roughness and material removal rate

The ultrasonic amplitude in the test is 6μm, 8μm, 10μm, 12μm and 14μm respectively and the other finishing parameters are shown in Table 1. Single factor test for UAMAF is conducted. The effect of ultrasonic amplitude on surface roughness and material removal rate is shown in Figure 5.

![Figure 5. Effect of ultrasonic amplitude on surface roughness and material removal rate.](image)

As can be seen from Figure 5, the surface roughness decreases rapidly and the material removal rate increases remarkably as the ultrasonic amplitude increases. The surface roughness reduces from Ra0.26μm to Ra0.12μm, and the material removal rate increases from 7.6mg/h to 30.5mg/h, when the amplitude increases from 6μm to 14μm.

The reason for this phenomenon is that an increase of ultrasonic impulse is caused by the increase of ultrasonic amplitude, which results ultrasonic force to rise linearly. The cutting force of a single magnetic abrasive on workpiece consists of magnetic field force and ultrasonic force. The magnetic field force remains unchanged during finishing. Therefore, the cutting force of UAMAF rises linearly with the increase of ultrasonic amplitude, which improves the ability of magnetic abrasive to cut into workpiece. Workpiece surface material is removed quickly and the material removal rate rises. The impact energy between magnetic abrasives and workpiece surface are increased due to the increase of the ultrasonic amplitude at the same time. Plastic flow is enhanced from the wave peak to the valley of workpiece surface. The randomness of the magnetic abrasive trajectory is also increased, resulting in complex interleavings of the cutting trajectories between adjacent abrasives. Therefore, the surface roughness reduces significantly.

3.3. Effect of spindle speed on surface roughness and material removal rate

![Figure 6. Effect of spindle speed on surface roughness and material removal rate.](image)
The spindle speed in the test is 800r/min, 1000r/min, 1200r/min, 1400r/min, 1600r/min and 1800r/min respectively and the other finishing parameters are shown in Table 1. Single factor test for UAMAF is conducted. The effect of spindle speed on surface roughness and material removal rate is shown in Figure 6.

It can be seen from Figure 6 that the surface roughness decreases and the material removal rate increases in the beginning of finishing as the spindle speed increases. The surface roughness reaches the lowest Ra0.11μm, and the material removal rate achieves the highest 22.74mg/h, when the spindle speed is 1400r/min. The surface roughness rises rapidly and the material removal rate drops significantly, when the spindle speed increases further. The surface roughness increases to Ra0.21μm, and the material removal rate reduces to 9.85mg/h, which is 57% lower than 22.74mg/h, when the spindle speed is 1800r/min.

The reason for this phenomenon is that the cutting length per unit time is increased due to the increase of spindle speed. So the surface roughness of the workpiece reduces and the material removal rate rises. The centrifugal force of the magnetic abrasive in the “abrasive brush” is enhanced, as the spindle speed increases. However, the magnetic abrasive will break away from the magnetic field force and fly out of the finishing area along the tangential direction of spindle rotation, when the centrifugal force is greater than the magnetic field force, resulting in a decrease of the amount of the abrasives involved in finishing in the “abrasive brush”. Therefore, the surface roughness increases and the material removal rate decreases, when the spindle speed increases continuously.

3.4. Effect of machining gap on surface roughness and material removal rate

The machining gap in the test is 0.75mm, 1mm, 1.25mm, 1.5mm and 1.75mm respectively and the other finishing parameters are shown in Table 1. Single factor test for UAMAF is conducted. The effect of machining gap on surface roughness and material removal rate is shown in Figure 7.

As can be seen from Figure 7, the surface roughness decreases and the material removal rate increases as the machining gap enlarges in the range from 0.75mm to 1.25mm. The surface roughness reaches the lowest Ra0.16μm, and the material removal rate achieves the highest 17.7mg/h, when the machining gap is 1.25mm. However, the surface roughness rises and the material removal rate drops rapidly, when the machining gap is greater than 1.25mm. The surface roughness increases from the lowest Ra0.16μm to Ra0.35μm, and the material removal rate reduces from 17.7mg/h to 8.8mg/h, when the machining gap increases from 1.25mm to 1.75mm.

The reason for this phenomenon is that magnetic abrasives are layered evenly along magnetic flux lines in machining gap. The magnetic pole collides with the magnetic abrasive of the uppermost layer, then ultrasonic vibration energy is transmitted layer-by-layer, and to the workpiece through the
lowermost layer of the magnetic abrasive finally in UAMAF. Therefore, the loss energy in ultrasonic vibration transmission increases linearly as the machining gap enlarges. However, the amount of magnetic abrasives in the machining gap increases at the same time. Magnetic abrasives are caused to collide with each other by ultrasonic vibration, resulting renewability and fluidity of the magnetic abrasive are enhanced, so the finishing ability is improved. Therefore, the surface roughness decreases, and the material removal rate increases as the machining gap enlarges in the range from 0.75mm to 1.25mm. Magnetic induction intensity in the machining gap decreases and the loss energy of ultrasonic vibration transmission rises further as the machining gap continues to enlarge, so the total cutting force composed of magnetic force and ultrasonic force decreases quickly. Therefore, the surface roughness increases and the material removal rate reduces as the machining gap increases from 1.25mm to 1.75mm.

4. Conclusions
A systematic experiment of UAMAF of titanium alloy is carried out in this research. The influence of machining time, ultrasonic amplitude, spindle speed and machining gap on surface roughness and material removal rate are studied and analysed. The conclusions are as follows:

1) Due to the vertex effect of UAMAF, the surface roughness decreases rapidly as the machining time increases. The surface roughness declines from the original Ra0.94μm to Ra0.10μm, after finishing for 30min. However, the surface roughness of workpiece is decreasing more and more slowly, because the vertex effect is weakened as the machining time goes further. The surface roughness reduces from Ra0.10μm to Ra0.08μm only, after finishing for another 20min. Therefore, to ensure the finishing quality, the optimal machining time is 30min.

2) Some diamond grains on magnetic abrasives are worn or fall off, so the finishing performance of magnetic abrasive is reduced, and the material removal rate is decreased approximately linearly as machining time increases. The material removal rate is 10.5mg/h at 50min, which is 55% lower than that of 10 min.

3) The cutting force of UAMAF is increased and the ability of magnetic abrasives to cut into workpiece is improved with the increase of ultrasonic amplitude. Workpiece surface material is removed quickly and the material removal rate rises. Plastic flow from the wave peak to valley of workpiece surface is enhanced and the randomness of the magnetic abrasive trajectory is increased due to the increase of the ultrasonic amplitude at the same time. So the surface roughness reduces quickly with the increase of ultrasonic amplitude. The surface roughness reduces to Ra0.12μm, and the material removal rate is up to 30.5mg/h, when the amplitude increases to 14μm. Therefore, to ensure the finishing efficiency and surface quality, high amplitude is used as much as possible.

4) The surface roughness of workpiece drops, and the material removal rate rises, because the cutting length per unit time is increased with the increase of spindle speed in the range from 800r/min to 1400r/min. However, the surface roughness increases rapidly, and the material removal rate decreases significantly, because more and more magnetic abrasives will break away from the magnetic field force and fly out of the finishing area and the amount of magnetic abrasives involved in finishing is reduced gradually as the spindle speed continues to increase. Therefore, a reasonable spindle speed is 1400r/min. In this case, the surface roughness achieves the lowest Ra0.11μm, and the material removal rate reaches the highest 22.74mg/h.

5) The amount of magnetic abrasives in the machining gap increases as the machining gap enlarges in the range from 0.75mm to 1.25mm. Fluidity of abrasives is enhanced by ultrasonic vibration, which reduces the surface roughness, and increases the material removal rate gradually. However, magnetic induction intensity in the machining gap decreases and the loss energy of ultrasonic vibration transmission rises further as the machining gap continues to enlarge, which increases the surface roughness and reduces the material removal rate. Therefore, the optimum machining gap is about 1.25mm. In this case, the surface roughness reaches a minimum of Ra0.16μm, and the material removal rate achieves a maximum of 17.7mg/h.
Acknowledgments
The authors would like to acknowledge the financial support for this research from National Natural Science Foundation of China (No. 51505057), Scientific Research Project of Education Department of Liaoning Province (No. JDL2017033), Natural Science Foundation of Liaoning Province (No. 20170540113) and High-level Talents Innovation Support Project of Dalian (No. 2017RQ049).

References
[1] Lu Y and Li XY 2012 Current status and development trend of machining of titanium alloy for aerospace. J. Aeron Manuf Technol. 14 55-57
[2] Chen Y, Liu ZQ and Wang XK 2012 Ultrasonic vibration assisted magnetic grinding process research. J. T Chin Soc Agric Mach. 19 294-298
[3] Jiao AY, Quan HJ and Chen Y 2013 Experimental study on ultrasonic magnetic composite grinding of titanium alloy cone holes. J. Chin J Mech Eng-en. 19 114-119
[4] Ma FJ, Tao DS, Gong C, Kang RK, Zhang SF and Sha ZH 2016 Technology of magnetic abrasive finishing in machining of difficult-to-machine alloy complex surface. J. Journal of Hebei University of Science and Technology. 37 449-456
[5] Lu YP, Ma J and Zhang JQ 2007 Ultrasonic magnetic abrasive composite grinding technology. J. Journal of China Coal Society. 5 552-556
[6] Ma J 2007 Study on ultrasonic magnetic composite grinding of mold surface. J. electromachining & Mould. 3 59-62
[7] Lu YP, Ma J and Zhang JQ 2007 Ultrasonic magnetic abrasive composite grinding technology. J. Journal of China Coal Society. 5 552-556
[8] YUN H, HAN B and CHEN Y 2016 Internal finishing process of alumina ceramic tubes by ultrasonic-assisted magnetic abrasive finishing. J.International Journal of Advanced Manufacturing Technology. 85 727-734
[9] Mulik R and Pandey P 2010 Mechanism of Surface Finishing in Ultrasonic-Assisted Magnetic Abrasive Finishing Process. J. Advanced Manufacturing Processes. 25 1418-1427
[10] Mulik R and Pandey P 2011 UAMAF of hardened AISI 52100 steel using unbonded SiCabrasives. J. International Journal of Refractory Metals and Hard Materials. 29 68-77