ISSN 1392–1207. MECHANIKA. 2017 Volume 23(6): 916–922

Investigation of Surface Integrity and Fatigue Performance of TC4 Titanium Alloy in Centrifugal Barrel Finishing

Xiuhong LI*, Wenhui LI, Shengqiang YANG*****
**College of Mechanical Engineering, Taiyuan University of Technology, Taiyuan, Shanxi, China,030024,*
Shanxi Key Laboratory of Precision Machining, Taiyuan, Shanxi, China, 030024, E-mail: xhli7489@sina.com
***College of Mechanical Engineering, Taiyuan University of Technology, Taiyuan, Shanxi, China, 030024*
Shanxi Key Laboratory of Precision Machining, Taiyuan, Shanxi, China, 030024, E-mail: wenhui_li7190@126.com
****College of Mechanical Engineering, Taiyuan University of Technology, Taiyuan, Shanxi, China, 030024*
Shanxi Key Laboratory of Precision Machining, Taiyuan, Shanxi, China, 030024, E-mail: tutysq@263.net.cn

crossref http://dx.doi.org/10.5755/j01.mech.23.6.19849

1. Introduction

Titanium alloys, an alloy which possesses good properties i.e., high specific strengths, low elastic modular, excellent high temperature performance, high corrosion resistance, and biocompatibility, are widely applied in many military or civil fields including aerospace, automotive industry, medical engineering, and etc. [1]. Because aviation engines and steam turbine are thermodynamic machinery with high durability bearing harsh aerodynamic load, mechanical load and high temperature load, the blade subjects to low cycle loading caused by centrifugal force and high cycle loading induced by all kinds of high frequency vibration, which leads to fatigue damage of the blade [2, 3]. In order to improve the service performances of titanium alloys resulting from low hardness, poor wear resistance and fatigue strength in industry application, the surface treatment and finishing are necessary for titanium alloys to make their surface integrity and fatigue performance better [4-8]. Up to now, more researches concerned with shot peening and carburizing improving the fatigue performance of titanium alloy. Gao Y.K. reported the influence of shot peering, laser shock peening, and low plasticity burnishing on surface integrity and fatigue performance of TC4 Titanium alloy [9]. Cao X.Z. and Wang Y.M. investigated influence of integrity on fatigue property of Ti6Al4V alloy by shot peening, and analysed the strengthening mechanism of shot peening increasing the fatigue limit [10-11]. Hui L. et al. analysed residual stress, micro-hardness and microstructure of ultrasonic squeezed TC6 titanium alloy [12]. Yang J. et al. simulated the fatigue performance of TC4 titanium alloy by laser shock peening [13]. Zhecheva A. et al. changed the microstructure and performance of titanium alloy by nitriding [14]. Chang X.D. et al. indicated the influence of the composite treatment via carburizing and shot peening on the surface integrity of 18Cr2Ni4WA steel, and discussed the action rules of the composite strengthening treatment, and clarified the internal relation between the surface integrity and the fatigue performance of the gear steel by the composite strengthening treatment [15]. Research results show that whether shot peening, or laser peening, or nitriding, or composite processing would increase the surface roughness of the workpiece, which leads to the surface damage and low fatigue life [16-18].

The barrel finishing is a polishing technique by which lots of parts or components made from metal or other materials can be economically processed. During the barrel finishing, free or non-free parts or components are placed in a container with compound solutions, water and media having aggressive cutting capabilities. Through certain motion of the container or/and components, energy is transferred to the media and components, which improves surface geometry feature and physical-mechanical property of the components. The barrel finishing has good processing effect, strong adaptability, low cost and little environmental pollution, and has been practically in realizing mass finishing. Yang S.Q. reported the influence of barrel finishing on the surface integrity of Q235A steel, and it can be seen from the test data that the barrel finishing can improve the surface integrity of Q235A steel. At present, a few scholars presented the application of barrel finishing in the blade of aviation engine [19-21].

Titanium alloy is often used as the material of the blade of aviation engine. Therefore, this paper explores the influence of centrifugal barrel finishing on the surface integrity and the fatigue performance of TC4 titanium alloy, and clarifies the internal relation between the surface integrity and the fatigue strength, and provides the basis for improving the service performance of the blade of aviation engine.

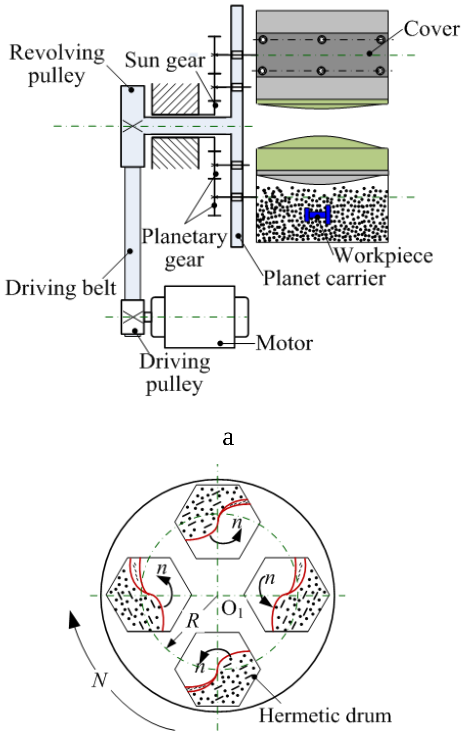
2. Experiment

2.1. Experimental equipment

Fig. 1 shows the schematic of horizontal centrifugal barrel finishing equipment 2M3160. As shown in Fig. 1, torque developed by an AC electric motor serving as a drive source is transmitted via a V-belt driving mechanism, drive pulley, drive belt and revolving pulley to the revolving shaft. The revolving shaft, which connected with the planet carrier serving as a revolving member, is rigid. Four rotating shafts are arranged circumferentially on the planet carrier at intervals of 90 degrees so as to be rotated relative to the planet carrier. Each horizontal rotating shaft is rotatable supported by bearings which are secured on the planetary gear. When the AC electric motor is started, each hermetic drum rigid connected with the rotating shaft is rotated on the planet carrier while being revolved together with the planet carrier with the rotation of the revolving shaft. For the developed equipment, the drum volume is designed to be 15L. And the power of the AC electric motor 3kW, its rotate speed can be adjusted by the variable-frequency drive. In addition, the transmission ratio n/N of the developed equipment is -1.

Fig. 2 shows the photo of centrifugal barrel finishing equipment 2M3160. On centrifugal barrel finishing equipment four drums are mounted on the periphery of a turret. The turret rotates at a given speed in one direction, while the drums rotate at a slower speed in the opposite direction. About 30%-70% of each drum capacity is filled with a mixture of compound solutions, water, workpieces and media having good cutting capabilities. Rotation of the drums creates a high centrifugal force and forced flow of the media, which impact, roll and slide each surface of the workpieces, and realize finishing of all surfaces of workpieces. The specific equipment parameters are listed in Table 1.

Under the condition of the stress ratio 0.1, the tensile fatigue experiments of finishinged and unfinishinged workpieces were carried out in GPS-100 fatigue testing machine. The GPS-100 fatigue testing machine is shown in Fig. 3.



a

b

Fig. 1 Schematic of the developed horizontal centrifugal barrel finishing equipment: a - front view, b - left view

Fig. 2 Centrifugal barrel finishing equipment

Fig. 3 GPS-100 fatigue testing machine

Table 1

Equipment parameters of centrifugal barrel finishing

Power	3 kW
Speed	180 r/min
Number of Drum	4
Capacity of Each Drum	15 Litre
Ratio of Turret Speed to Barrel Speed	-1

2.2. Media and compound solutions

The main function of media is to abrade or burnish the edges and surfaces of components, and improve the surface integrity of components. Not only do the types, sizes, and shapes of media affect surface roughness, residual stress, and surface hardening layer, but also finishing efficiency. The media in experiments are sintered spherical alumina grinding block, which are shown in Fig.4.

Fig. 4 Spherical alumina media

The main role of compound solutions is to modify the lustre or colour of the workpieces. In addition, they can improve finishing effects and efficiency. LC-10 liquid is used as compound solutions during the experiments.

2.3. Workpieces

The material of workpieces is TC4 titanium alloy during the experiments. The main chemical components are listed in Table 2, and the main mechanical properties are shown in Table 3. Initially all these workpieces are ground to an average initial surface roughness value of 1.18±0.03μm. Change in *Ra* value is defined as:

$$\Delta Ra = \text{Initial } Ra - \text{Final } Ra \quad (1)$$

Fig. 5 shows the structure and size of the test specimen.

Table 2

Main chemical components of TC4 titanium alloy (wt.%)

Al	V	Fe	O	C	N	H	Ti
5.5~6.8	3.5~4.5	0.30	0.20	0.10	0.05	0.015	Bal.

Table 3

Main mechanical properties of TC4 titanium alloy

Tensile strength, MPa	Yield strength, MPa	Young's modulus, GPa	Elongation, %
887	830	114	14

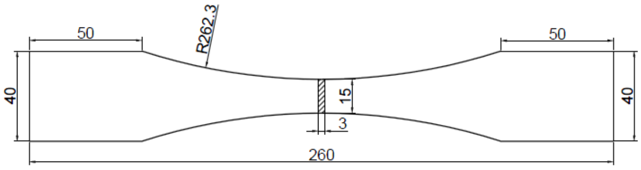


Fig. 5 Structure and size of test specimen

2.4. Experimental procedure

In the centrifugal barrel finishing, the diameter, the volume capacity and finishing time of the media are important for surface roughness. Five diameters of media are investigated in this study, including 3 mm, 5 mm, 6mm, 8 mm, and 10 mm. Four volume capacities of media, 40%, 50%, 60%, and 70%, are used in the experiment. Nine finishing times were examined.

3. Results and discussion

3.1. Surface roughness

Fig. 6 shows the relationships between the change in the values of surface roughness ΔRa and finishing time at various diameters of media. Fig. 7 is one of the three-dimensional topographies after finishing.

This experiment was conducted using 50% of volume capacity. During initial processing, the change in the value of surface roughness increases with the finishing time, because the burrs, sharp corners and convex peaks on the surface of the workpiece are effectively removed under the co-action of collision, rolling, and sliding. When the finishing time reaches a certain value, the surface is smooth, and the surface is hardened. As a result, the value of surface roughness changes slowly over time. With the increase of the diameter of finishing media, the normal force between media and workpieces increases, and rolling effect enhances, and thus the change in surface roughness value ΔRa increases with the increase of the diameter of media. When the diameter of media reaches to a certain value, the change in the value of surface roughness decreases due to micro-pits caused by the large normal force. The optimum changes in the values of surface roughness with the diameters of 3, 5, 7, 8 and 10 mm were 0.345, 0.455, 0.54, 0.623, and 0.59 μm, respectively.

Fig. 8 shows the relationships between the change in the values of surface roughness ΔRa and finishing time at various volume capacities. This experiment was conducted using 8mm of diameter of media. When the volume capacity is smaller, the rolling amplitude of media within the drum is larger, and the collision action between media and workpieces is enhanced. As a result, the indentations appear on the surface of the workpiece resulting in the smaller change of the surface roughness value. But the excessive volume capacity would affect finishing effect due to the local relative static between media and workpieces. When the volume capacity is appropriate, sliding chances between the media and workpieces increase, which produce better finishing effects. The optimum changes in the values of surface roughness with the volume capacities of 40, 50, 60, and 70% were 0.48, 0.623, 0.52, and 0.458 μm, respectively.

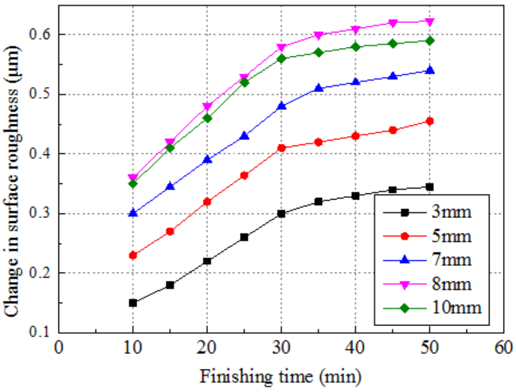


Fig. 6 Effect of finishing time on change in surface roughness at various diameter of media with volume capacity: 50%

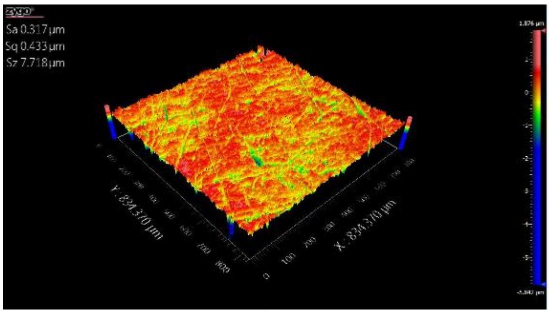


Fig. 7 Three-dimensional topography after finishing

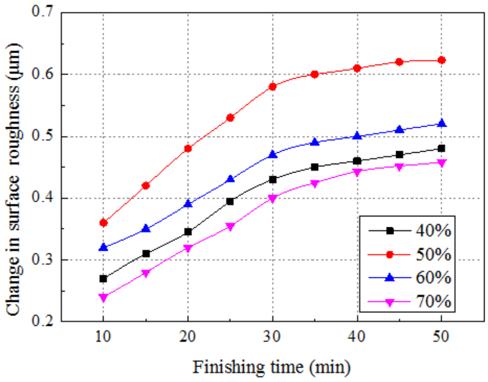


Fig. 8 Effect of finishing time on change in surface roughness at various volume capacity with diameter of media 8 mm

3.2. Residual compressive stress

Fig. 9 shows the relationships between the residual compressive stress and finishing time at various diameters of media. This experiment was conducted using 50% of volume capacity. During initial processing, the residual compressive stress improves with the finishing time, because the intense plastic deformation occurs with the increase of collision times between media and workpieces. As a result, the residual compressive stress increases significantly. When the finishing time reaches a certain value, the plastic deformation tends gradually to be saturated, and the change of the residual compressive stress is not obvious. The maximum residual compressive stress reaches to -462 MPa. With the increase of the diameter of finishing media, the collision action between media and workpieces increases resulting in producing larger plastic deformation and residual compressive stress on the surface of the workpieces.

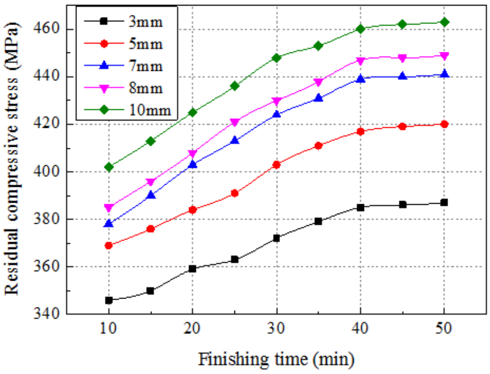


Fig. 9 Effect of finishing time on residual compressive stress at various diameters of media with volume capacity 50%

Fig. 10 shows the relationships between the residual compressive stress and finishing time at various volume capacities. This experiment was conducted using 8mm of diameter of media. When the volume capacity is less than 50%, the rolling amplitude of media within the drum is larger, and the collision action between media and workpieces is enhanced with the increase of the volume capacity resulting in significant plastic deformation and larger residual compressive stress. When the volume capacity exceed a certain value, the rolling amplitude of the media decreases with the increase of the volume capacity, which lessens the collision action between media and workpieces, leading to the smaller residual compressive stress.

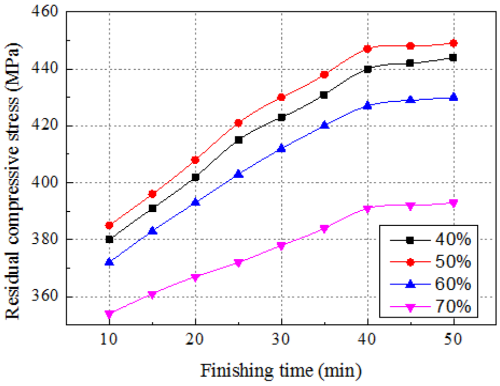


Fig. 10 Effect of finishing time on residual compressive stress at various volume capacities with diameter of media: 8mm

3.3. Micro-hardness

Fig. 11 shows the change of the micro-hardness on the surface of the workpiece along the depth direction. This experiment was conducted using 8mm of diameter of media and 50% of volume capacity. Measurement of the Vickers' hardness was used to control the surface properties before and after finishing by Mitutoyo hardness tester HM-102. The maximum load for the experiments was 1 kgf, and the distance between any two neighbouring indentations was at least 10 µm. The shear slip deformation of the material is large on the surface of the workpiece due to the strong collision action between media and workpieces, which produces high micro-hardness. As shown in Fig. 11, the surface hardness reaches to 420 HV from initial 338HV, increasing by 24.3%. The larger the distance from the finished surface is, the weaker the collision action between media and workpieces is, and the smaller shear slip deformation and micro-hardness are. When the distance from the finished surface reaches a certain value, the surface of the workpiece almost no longer has shear sliding deformation, and the micro-hardness value basically remains unchanged.

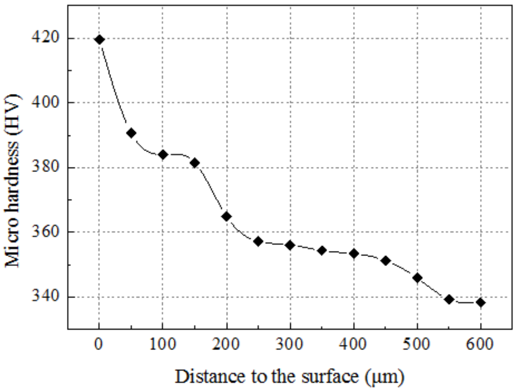
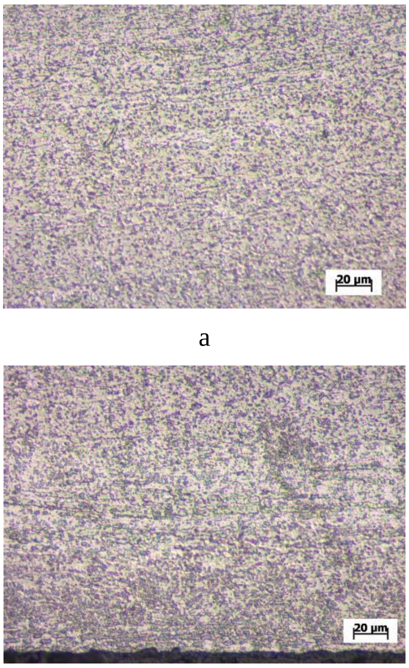


Fig. 11 Micro-hardness of the work-piece along the depth direction

3.4. Microstructures

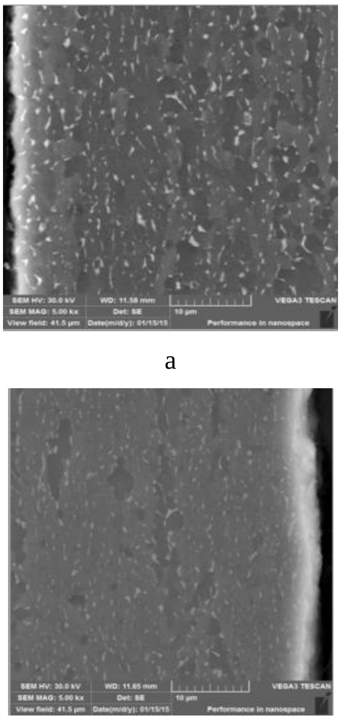
This experiment was conducted using 8 mm of diameter of media, 50% of volume capacity, and 50 min of finishing time. Fig. 12 shows the metallographic structure before and after the finishing. It can be seen that the microstructure of the sample is homogeneous, and the grains are coarser before than after finishing. After finishing, the grain of the surface stretches due to the compression deformation relative to the substrate, which produces a metamorphic layer. As a result, the microstructure of the material is not the same as that of the substrate. The plastic deformation reduces gradually from the surface to the substrate through the whole thickness of the specimen, and changes in gradient. There is no obvious interface between the deformation layer and the substrate. The deformation layer mainly occurs within 40 µm-60 µm from the surface because of severe cyclic plastic deformation of the surface structure under the repeated impact of media. The larger the distance from the surface is, the weaker the collision action of media is, and the smaller the grain deformation is.



a

b

Fig. 12 Metallographic structure of samples before and after finishing time(X500): a - before finishing, b - after finishing



a

b

Fig. 13 Cross-section SEM micrographs of samples before and after finishing time: a - before finishing, b - after finishing

Fig. 13 shows the cross-section SEM micrographs of samples before and after finishing time. As shown in Fig. 13, a that microstructures of the sample keep uniform before finishing. But the surface microstructure has produced repeating plastic deformation due to the collision action of the media. A mass of dislocations and dislocation cells form during plastic deformation while some twins form simultaneously on the surface of the samples. The grains refine obviously, and the grain boundary is not clear. This substructure can prevent dislocation slipping during fatigue. So the fatigue performance is improved.

Fig. 14 shows the XRD spectra of TC4 before and after finishing. As can be seen from the comparison graph, the main crystal faces of (100), (002) and (101) at 35.03, 38.42 and 40.07 attributed to α-titanium alloy are found. The (002) diffraction peak is the main peak before finishing, and (101) becomes the main peak after finishing, which shows that the preferential texture of TC4 titanium alloy has changed from (002) to (101) induced by finishing. It can induce interior residual compressive stress due to the shift of the distraction peak toward the left after the finishing. The XRD data indicate that the centrifugal barrel finishing causes the XRD peaks to broaden, the grain size to refine, and the internal dislocation density to increase. These results are consistent with the metallographic observation.

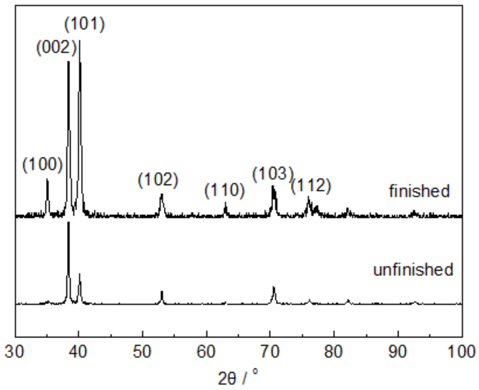


Fig. 14 XRD spectra of TC4 before and after centrifugal barrel finishing

3.5. Influence of centrifugal Barrel finishing on fatigue performance of TC4 titanium alloy

The samples were finished using 8mm of diameter of media, 50% of volume capacity, and 50 min of finishing time, and the tension-tension fatigue experiments are conducted on a high-frequency fatigue test machine under the conditions of 0.1 of ration and 103.3 Hz of frequent. Fig. 15 shows the change of fatigue performance of TC4 titanium alloy before and after finishing. As can be seen from these data, centrifugal barrel finishing can remarkably improve the fatigue performance of TC4 titanium alloy resulted

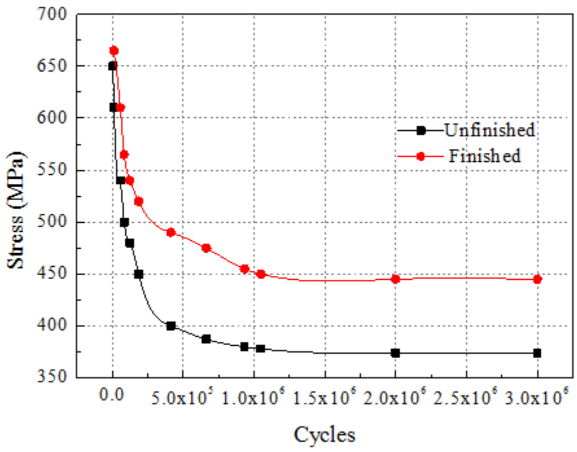
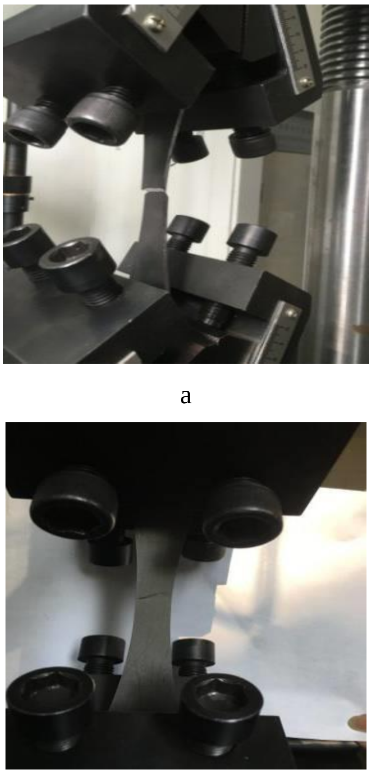


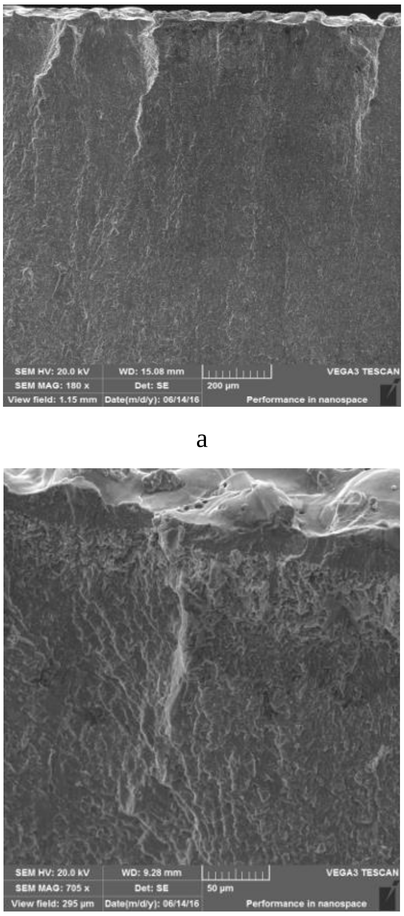
Fig. 15 Change of fatigue performance of TC4 titanium alloy before and after finishing



a

a

Fig. 16 Photos of fatigue fracture: a - before finishing, b - after finishing



a

b

Fig. 17 SEM images of fatigue fracture: a-before finishing, b-after finishing

good surface quality, high micro-hardness, and appropriate residual compressive stress. The fatigue limit reaches to 445 MPa from initial 374 MPa, increasing by 18.98%. The fatigue life increases from 10762 times to 56220 times under the stress of 610 MPa.

Fig. 16 is the photos of the fatigue fracture. Fig. 17 is the SEM images of fatigue fracture. As can be seen from Figs. 16 and 17, the initiation location of the fatigue cracks is on the free surface for the unfinished workpiece, but the fatigue crack initiation change from the surface to the sub-surface after finishing. This is because the surface hardening resulting from finishing can increase the fatigue resistance of the workpiece, and the decrease of the surface roughness can effectively reduce the crack initiation on the free surface. The grain refinement and the residual stress prevent cracks from propagating. So the fatigue performance of TC4 titanium alloy is improved after finishing.

4. Conclusions

An experimental investigation was carried out to study the effect of main technology parameters on the surface integrity parameters (surface roughness, residual stress, surface hardness and microstructure) and fatigue performance of TC4 titanium alloy. Based on the results and discussion, following conclusions can be drawn:

1. The centrifugal barrel finishing can comprehensively improve the surface integrity and fatigue performance of TC4 titanium alloy. The finishing effect is best under the condition of 8mm of diameter of media, 50% of volume capacity, and 50 min of finishing time.

2. The centrifugal barrel finishing would make the value of surface roughness decrease 0.623 μm, and the surface hardness reaches to 420 HV from initial 338 HV, increasing by 24.3%, and the maximum residual compressive stress reaches to – 462 MPa.

3. The fatigue limit reaches to 445 MPa from initial 374 MPa, increasing by 18.98%. The tensile fatigue life of TC4 titanium alloy increases from 10762 times to 56220 times under the conditions of stress ratio of 0.1 and stress of 610 MPa.

Acknowledgements

This project is supported by National Natural Science Foundation of China (U510118), Provincial Natural Science Foundation of Shanxi (2017D121073) and Shanxi Provincial Programs for Science and Technology Development (2015031011-3).

References

1. **Gao, Y.K.** 2014. Theory and application of surface integrity. Chemical Industrial Press, Beijing.
2. **Zhang, X.D.; Li, X.H.; Li, W.H.;** et al. 2014. Numerical simulation analysis of the centrifugal roll finishing of Titanium alloy, Surface Technology 5: 11-15 (in Chinese).
3. **Zhao, Z.H.; Chen, W.; Wu, T.Y.** 2011. Fatigue life predictions under high and low combined cycle loading, Journal of Mechanical Strength 33(4): 629-632 (in Chinese).
4. **Guo, D.M.; Sun, Y.W.; Jia, Z.Y.** 2014. Methods and

research progress of high performance manufacturing, Journal of Mechanical Engineering 50 (11): 119-134 (in Chinese).
https://doi.org/10.3901/JME.2014.11.119.

5. **Hashimoto, F.; Yamaguchi, H.; Krajnik, P.;** et al. 2016. Abrasive fine-finishing technology, CIRP Annals-Manufacturing Technology 65(2): 597-620. https://doi.org/10.1016/j.cirp.2016.06.003.
6. **Sabih, A.; Radziszewski, P.; Mullany, I.** 2017. Investigating grinding media differences in microstructure, hardness, abrasion and fracture toughness, Minerals Engineering 103-104: 43-53. https://doi.org/10.1016/j.mineng.2016.08.014.
7. **Saraswathammaa, K.; Jhab, S.; Rao, P.V.** 2015. Experimental investigation into Ball end magnetorheological finishing of silicon, Precision Engineering 42: 218-223. https://doi.org/10.1016/j.precisioneng.2015.05.003.
8. **Osa, J.L.; Sanchez, J.A.; Ortega, N.;** et al. 2016. Discrete-element modelling of the grinding contact length combining the wheel-body structure and the surface-topography models, International Journal of Machine Tools & Manufacture 110: 43-54. https://doi.org/10.1016/j.ijmachtools.2016.07.004.
9. **Gao, Y.K.** 2016. Influence of different surface modification treatments on surface integrity and fatigue performance of TC4 Titanium alloy, ACTA Metallurgica Sinica 52(8): 915-922. http://doi/10.11900/0412.1961.2015.00628.
10. **Cao, X.Z.; Han, X.Q.; Gai, P.T.** 2014. Influence of surface integrity on fatigue property of Ti6Al4V alloy, Aeronautical Manufacturing Technology 14: 95-98 (in Chinese).
11. **Wang, M.; Lu, Sh.; Gu, Y.X.;** et al. 2013. Experiment of effect of shot peening strengthening on TC11 alloy simulation blade's HCF life, Journal of Aerospace Power 38: 507-512 (in Chinese).
12. **Hui, L.; Yang, L.Q.; Xu, L.;** et al. 2016. Effect of ultrasonic squeeze strengthening on fatigue behavior of TC6 titanium alloy, Heat Treatment of Metals 41(9): 100-102 (in Chinese).
13. **Yang, J.; Zhou, J.Z.; Huang, S.;** et al. 2013. Numerical study on fatigue property of TC4 titanium alloy by laser shock peening, Applied Laser 33: 131-138 (in Chinese). https://doi.org/10.3788/AL20133302.131.
14. **Zhecheva, A.; Sha, W.; Malinov, S.; Long, A.** 2005. Enhancing the microstructure and properties of titanium alloys through nitriding and other surface engineering methods, Surface & Coatings Technology 200(7): 2192-2207. https://doi.org/10.1016/j.surfcoat.2004.07.115.
15. **Chang, X.D.; Liu, D.X.; Cui, T.F.;** et al. 2013. Influence of Carburizing Combined with shot peening on surface integrity and fatigue behavior of 18Cr2Ni4WA steel, Mechanical Science and Technology for Aerospace Engineering 32: 1584-1590 (in Chinese).
16. **Kravchenko, B.A.; Ivanov, Yu, L.; Nosov, N.V.,** et al. 1983. Surface quality in vibrocontact polishing with diamond belts, Soviet Aeroautics 26: 81-83.
17. **Chen, Y.J.; Bu, Z.Y.; Jin, J.S.** 2016. Influence of shot peening combined with vibration finishing on fatigue performance of TC4 titanium alloy, Surface Technology 45(11): 62-66.
18. **Li, X.B.; Shi, Y.Y.; Zhao, P.B.;** et al. 2012. Polishing force control technology of aero-engine blade in belt polishing, Computer Integrated Manufacturing Systems 18(6): 1209-1214 (in Chinese).
19. **Zhang, J.L.; Li, W.H.; Yang, S. Q.;** et al. 2014. Dynamic analysis of the media in centrifugal barrel finishing, Advanced Materials Research, 1027: 230-234. https://doi.org/10.4028/www.scientific.net/AMR.1027.230.
20. **Li, W.H.; Yang, S.Q.; Liu, G.L.; Ren, H.** 2013. Theoretical analysis and experimental research on barrel finishing for special shaped and large size shaft parts, Vehicle Engine (5): 87-92 (in Chinese).
21. **Yang, S.Q.; Wang, Y.W.; Yang, S.C.** 1999. The comprehensive improvement of skew spindle high pressure finishing to parts' surface integrity, China Mechanical Engineering 10: 626-629 (in Chinese).

Li, Wenhui Li, Shengqiang Yang

INVESTIGATION OF SURFACE INTEGRITY AND FATIGUE PERFORMANCE OF TC4 TITANIUM ALLOY IN CENTRIFUGAL BARREL FINISHING

Summary

This paper aims to improve the surface integrity and fatigue performance TC4 titanium alloy. Centrifugal barrel finishing was taken to enhance surface performance of TC4 titanium alloy. Centrifugal barrel finishing experiments and tensile fatigue test were conducted for investigating the surface integrity and fatigue performance of TC4 titanium alloy. The surface integrity including surface roughness, residual stress, micro-hardness, and microstructure were investigated under different conditions by different methods. The tensile fatigue performance were tested and the fatigue fracture were analysed by SEM. The results show that the centrifugal barrel finishing can make surface roughness value decrease 0.623 μm, and the surface hardness reaches to 420 HV from initial 338 HV, increasing by 24.3%, and the maximum residual compressive stress reaches to -462MPa. The fatigue limit reaches to 445 MPa from initial 374 MPa, increasing by 18.98%. The fatigue life of TC4 titanium alloy increases from 10762 times to 56220 times under the conditions of stress ratio of 0.1 and stress of 610 MPa. The centrifugal barrel finishing can comprehensively improve the surface integrity and tensile fatigue performance of TC4 titanium alloy.

Keywords: centrifugal barrel finishing, fatigue performance, surface integrity, residual stress.

Received January 08, 2017
Accepted December 07, 2017