Micro-stiffener surface characteristics with belt polishing processing for titanium alloys

XIAO Gui Jian[1, a *],Dai Wentao[1, b] HUANG Yun[1, c],and Liu Ying[1,d]

[1] The State Key Laboratory of Mechanical Transmissions, Chongqing University, Chongqing 400044, China

[a]xiaoguijian@cqu.edu.cn, [b]daiwentao6666@163.com, [c]yunhuang@samhida.com, [d]lyjfb@163.com

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Abstract. Titanium alloys are extensively used in the design of key rotatable parts of aero-engines, such as the blade and blisk, and the final surface integrity has a significant influence on its fatigue life. It is very important to create optimal surface integrity to improve fatigue life by using advanced manufacturing technology, under the requirements of surface integrity for titanium alloy parts. In this paper, the micro-stiffener belt polishing (MSBP) method is presented. The formation rules of the surface characteristics are analysed according to material removal under flexible contact conditions. The surface topography is expressed by the wavelet transform and polishing moving model, following which the surface topography is analysed by means of comparison with the electron microscope test results. The distribution of different depth residual stresses is predicted by finite element analysis. The surface profile is obtained by a contour-graph, based on which the surface roughness distribution is obtained. The experimental results demonstrate that the surface characteristics, surface topography, surface roughness and residual stress all meet the requirements. Furthermore, the micro-stiffener surface characteristics are superior to those of the smooth surface, particularly in terms of consistency.

Introduction

Titanium alloys, with effective material characteristics including low density, high strength under high temperature and suitable corrosion resistance under a high-pressure interactive environment, are widely used in the design of key rotatable parts of aero-engines, such as the blade and blisk. However, components with complex surfaces and difficult-machining-material design specifications may induce manufacturing challenges, particularly when precision manufacturing processing is needed to enable their compliance with tight aero-engine industrial standards for high workpiece surface integrity characteristics and profile precision [1]. However, owing to the challenges of heat loss and serious grain wear, burns and micro-cracks easily appear on the surface during the titanium alloy grinding process, which has a significant influence on surface integrity.

Axinte et al. reported on the influence of polishing methods/strategies on the quality and integrity of workpiece surfaces obtained following different polishing methods applied to Ti-6-4 heat-resistant alloy [2]. Du et al. [3] investigated the metamorphic layer is by means of an optical microscope, transmission electron microscopy and high resolution transmission electron microscopy, and the grinding surface integrity of the superalloy GH4169 was improved. And then, the influence of abrasive grain geometry on the friction coefficient and wear rate →א studied, according to the contact mechanism between the belt and the surface, following which a 3D model with multi-asperity abrasive wear was used to express real-world rough surfaces. Rech et al. [4] generated residual stresses by means of belt finishing using two complementary methods: an experimental X-ray diffraction characterization and an understanding of the experimental results. Zhao et al. improved the surface integrity and roughness of the blade by optimizing the parameters in the polishing process with surface roughness prediction [5]. Ozel [6] determined that the residual stresses become more tensile at the surface, while white layers become more visible, owing to the increasing plastic deformation and temperature gradients during machining. Zhu et al. [7] introduced a microscopic scale of the ploughing force model to study on belt grinding mechanisms. Xiao et al. [8] introduced an integrated polishing method to improve the surface integrity of a compressor blade using the method of belt and bob polishing. The results indicate that the surface texture was smooth, with a surface roughness of <0.35 μm, while the surface residual stress in the blade was between -89 and -410 MPa. Wang et al. [9] studied optimization of the grinding parameters when grinding the GH4169 nickel-based superalloy by using a single crystal corundum grinding wheel, as well as the influence rules of grinding parameters on the surface topographic characteristics, including surface roughness, topography, and micro-hardness, and the residual stresses of the surface integrity. Xu et al. [10] performed grinding experiments to investigate the grinding surface properties of titanium alloy TC4-0T using SEM, EDS, XRD, and so on. Kermouche et al. [11] induced the residual stress field through the scratch of a single round abrasive grain and investigated this by means of an implicit finite element analysis. Ulutan, Dreier and Denkena [12] described a novel method for measuring residual stress in plates with little effort, which is derived from the well-known Layer removal method and utilizes a machine tool with a standard probing device.

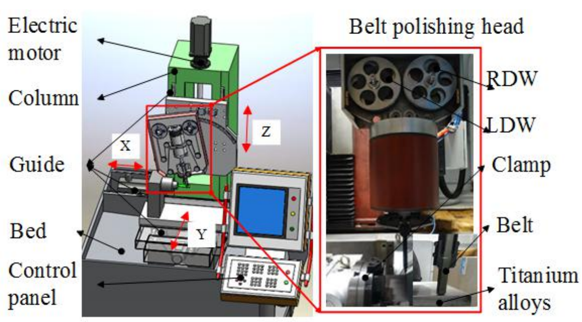
From the above analysis on the current research into the surface integrity of titanium alloy grinding, it can be seen that surface integrity is improved by the optimization of process parameters. Without the combination of fatigue analysis, the surface topography has a mainly transverse texture; furthermore, the surface roughness and residual stress of this texture can easily form micro-crack, surface microstructures, and other defects, in which case the fatigue life would be affected.

Therefore, in this paper, the micro-stiffener belt polishing (MSBP) method is presented based on the influence rule of the thin-plate stiffener on the bending life and the micro-crack principle, following which the surface characteristics and its formation of titanium alloy MSBP are revealed by comparing analyses of the different polishing processes, using a numerical simulation and advanced measuring method.

Experiment and methodology

Experimental setup. The experimental setup, as illustrated in Figure 1(a), was designed and manufactured by the authors, and comprises six electric motors, a belt polishing head, columns, a guide bed, and computerized numerical control (CNC) panel. The titanium alloys plate is used for experimental research, while the X-axis, Y-axis, and Z-axis are used only for polishing, although there are six moving axes in this experimental setup.

Linear displacement sensors were installed on each axis. The laser interferometer was used to test the kinematic accuracy for the movement of the X-axis, Y-axis, and Z-axis, while closed-loop control of the belt polishing was achieved by position information feedback to the CNC system, relating to the moving point, following which the errors were compensated. The movement accuracies of the X-axis, Y-axis, and Z-axis following compensation are displayed in Figure 1.



Items	Parameters
X/Y/Z accuracy	0.01 mm/0.01 mm/0.01 mm
X/Y/Z feeding speed	0~15 m/min
X/Y/Z repeatability	0.008 mm/0.005 mm/0.005 mm

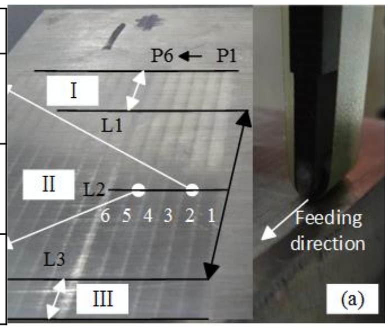


Figure 1 Polishing equipment and Precision parameters

The SIEMENS D425 system was used to realise the synchronous control of two servo motors and the reciprocating motion, following which the belt polishing process of the reciprocating and high-speed rotation were achieved. According to the control method for the belt polishing process, a motor control model was developed by SIMOTION SCOUT V4.4, and the experimental debugging was established by the WinCC FLEXCIBEL.

Experimental methodology. The blisk was installed on a high-precision turntable, the rotary motion of the worktable is realized by connecting the blisk and worktable. The blisk sample from an aircraft engine was used. The blisk was made from precision-milled, Ti-6-4 heat-resistant alloy. The parameters that were used in this experiment were rotation speed of 15m/s, feeding speed of 0.5m/min, and grinding pressureof 6N. The belt and wire-wheel is shown in Firue1, and other important parameters were as follows:

(a) The belt polishing process used a backward feed direction and 3M nylon belts (5 mm width) with the following grades: (i) randomly distributed grains; and (ii) grains formed into pyramids.

(b) The wire-wheel polishing process used a backward feed direction and off-the shelf and custom 10 mm diameter tools made from the following 3M abrasive materials/grades: SiC Scotch-Brite 2 Fine; and polycrystalline diamond (PCD74—mesh 250).

The blisk full-area test planning is as follows:A1 and A6 are the testing points for the surface roughness and topography, A2 and A4 are the CC testing points, and A3 and A5 are the V testing points. L1–L6 represents the profile precision testing line.A three-coordinate measuring instrument (Global silver 05.07.05) was used to measure the profile precision of the root-fillet of blisk after milling and polishing. The surface roughness was measured by a surface roughness instrument (Times, TR200), according to the profile shape of blade surface, the measurement length was 0.4 mm, and the evaluation length was 0.08 mm. The surface topography of the blade was tested by field-emission scanning electron microscopy.

Results and discussions

Surface topography characteristics. The belt grain topography was simulated based on numerical signal processing. Thereafter, the grain distribution was determined through processing of the curvature transformation and extracting noise on the numerical signal. Finally, the non-Gaussian belt grain topography was expressed by wavelet transform and 2D digital filtering technology. The surface topography was expressed by combing the belt polishing movement and belt grain topography, considering the processing parameters, including contact force, belt speed and feeding speed. The results are illustrated in Figures 2 and 3.

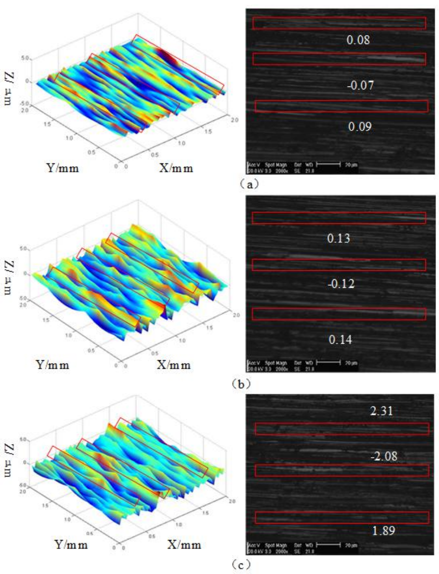


Figure 2 Micro-stiffener topography.

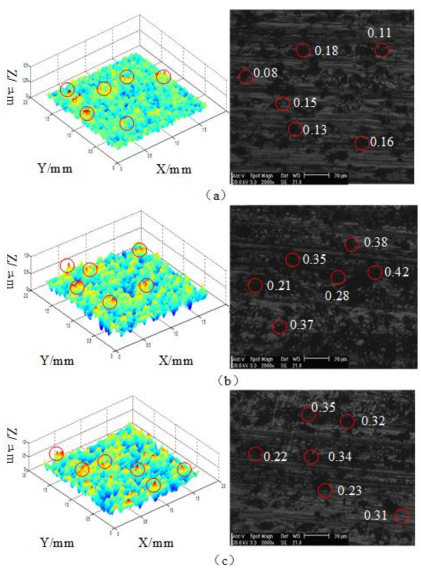


Figure 3 Smooth surface topography

The micro-stiffener surface topography is illustrated in Figure 2. The micro-stiffener was formed by belt processing of reciprocating movement. Compared to points 1 and 2, as indicated in Figures 3(a) and (b), the feature is not obvious, as the feeding speed, and simultaneously, the maximum Z, is increased from 0.09 to 0.14. When comparing points 1 and 3, the maximum Z reaches 2.31. Thus, in order to form a clear micro-stiffener, the contact force and feeding speed should be increased. The smooth surface topography is illustrated in Figure 3. The smoothness was formed by high-speed rotation belt polishing. Using the same forming rule as the micro-stiffener surface, the maximum Z was increased as the contact force and feeding speed increased. Owing to its characteristics, the surface is easily burned, and this phenomenon is improved when using reciprocating movement. The main reason for this is that the contact time between the belt grain and materials decreases with reciprocating movement.

Comparing the two different surface topographies according to the above analysis, the micro-stiffener surface topography characteristics are more obvious, and they also exhibit superior consistency in terms of topography shape. In contrast, the smooth surface is more complex, particularly regarding the topography features and distribution rules. Therefore, for the high-speed rotation belt polishing process, it is more difficult to control the surface topography characteristics.

Surface roughness characteristics. Surface roughness is an important parameter for measuring manufacture processing, particularly the polishing process.

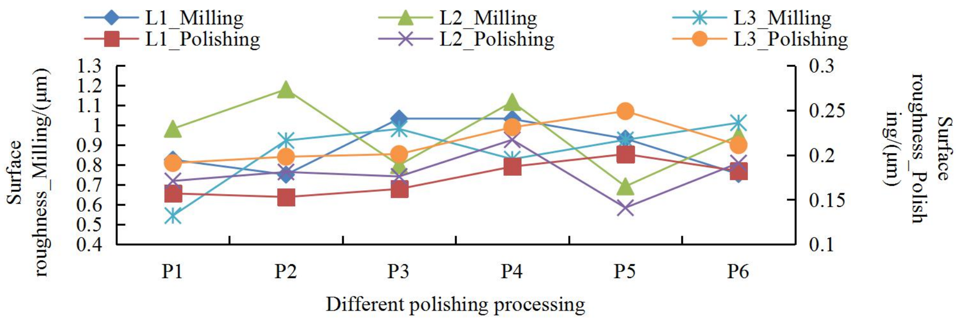


Figure 4 Surface roughness following milling and polishing processing.

The surface roughness values of P1, P2, and P3 are illustrated in Figure 5, and are between 0.153 and 0.201 following milling and polishing processing, while P4, P5, and P6 are between 0.142 and 0.249. Thus, the surface roughness is less than +0.25 μm, regardless of the method is used in this experiment, which satisfies the requirements of most titanium alloys parts, namely the blade, blisk, and so on. However, the surface roughness consistencies from P1 to P3 are superior to those of P4 to P5, which can also be observed in Figure 4, where the maximum profile depth consistency is superior. Not only the micro-stiffener formation on the surface, but also the surface roughness, meets the requirements, even more effectively than the smooth surface.

Surface residual stress characteristics. The residual stress in the layer depth, obtained by means of simulation analysis using the finite element method, is illustrated in Figure 5. The maximum influence layer depth of the surface residual stress is 2.83 μm for P1, P2, and P3; however, the maximum influence layer depth of the surface residual stress is 1.48 μm for P4, P5, and P6. Therefore, the influenced surface residual stress of different layer depths is greater with reciprocating polishing. Moreover, the influence depth would be increased with an increase in the contact force or decrease in feeding speed, as demonstrated by P1 and P3, P4 and P6, or P1 and P2, P4 and P5.

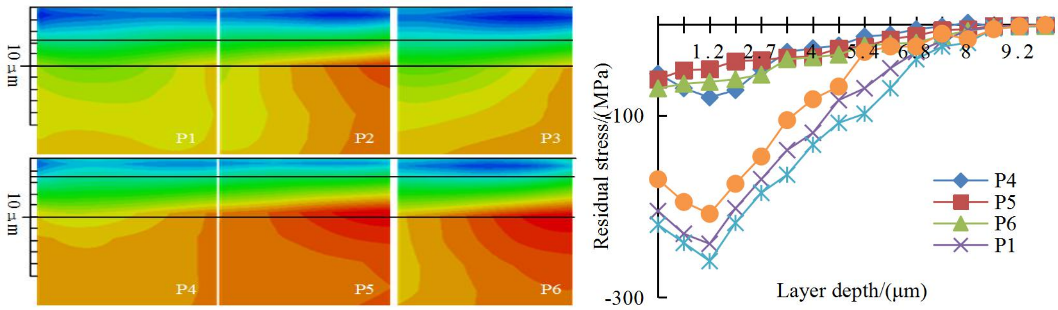


Figure 5 Residual stress in layer depth obtained by simulation analysis.

The X-ray projector was used to test the layer depth of the sectional surface residual stress, as illustrated in Figure 5. The maximum surface residual compressed stress in the layer depth is -286

MPa for P3. With the reciprocating polishing, however, the maximum surface residual compressed stress in the layer depth is -83 MPa for P6, and the maximum residual stress was obtained when the contact force increased. Therefore, the surface residual compressed stress of the micro-stiffener is far greater than that of the smooth surface. From the above analysis, the influence depth and degree of the surface residual stress is greater with reciprocating polishing, which is mainly because of the attacking characteristics of reciprocating polishing.

Summary

The micro-stiffener surface, manufactured by a reciprocating belt polishing process, exhibits superior surface integrity characteristics to the smooth surface. First, the micro-stiffener surface topography features are more obvious, and also exhibit improved consistency in terms of the topography shape. Second, the surface roughness is less than 0.25 μm; meanwhile, the consistency of the maximum profile depth is improved. Third, the influence depth and degree of the surface residual stress are bigger. Overall, the reciprocating belt polishing process method could be used in titanium alloy components in order to improve the fatigue life.

Acknowledgments

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