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Technical paper

Experimental research and modelling of life-cycle material removal in belt finishing for titanium alloy

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ABSTRACT

The use of heat-resistant titanium alloys for the manufacture of gas turbine engine components for aerospace/energy applications, including the blisk, blade, casing, and bling, has become a routine exercise. Belt finishing is a good method for the precision manufacturing of titanium alloy components. However, normal belt finishing with elastic contact and grain wear might pose manufacturing challenges, especially when finishing processes are needed to control the cutting depth, remove the machining marks and establish a required workpiece surface quality and profile precision. Information on efficient finishing and material removal modelling of belt finishing for such sensitive industrial applications is scarce.

This paper aims to establish a model of life-cycle material removal (LCMR) for a newly proposed method of BEF (belt efficient finishing) to realize the final precision finishing operation for components made of titanium alloy. Firstly, the theory model of LCMR is established by the curvature of LCMR for BEF based on the material removal mechanism of normal belt finishing. Secondly, the parametric mathematical models of LCMR for BEF of titanium alloy materials with flat and cylindrical surfaces are established by the method of least squares multiple linear regression analysis after orthogonal experimentation, and next, the F-test method is used to verify the significance of the model. Finally, the material removal of the BEF mechanism is analysed for different finishing parameters, conditions and movements with the single factor experiment method, and the parametric mathematical models of LCMR for BEF are simultaneously verified. Using this model, the life-cycle material removal can be predicted during belt efficient finishing of titanium alloy materials. The experimental and predicted results were in good agreement, and it could be concluded that the new method might be a viable process for finishing aero-engine components.

1. Introduction

With the characteristics of such factors as light specific gravity, high specific strength, good thermal strength in high temperatures, good toughness in low temperatures, and excellent resistance corrosion, the use of heat-resistant titanium alloys for the manufacture of gas turbine engine components for aerospace/energy applications, including the blisk, blade, casing, and bling, has become a routine exercise [1,2]. Titanium materials have the characteristics of active chemical properties and high strength and toughness, so grain wear, adhesion of chips and larger thermal stresses are easily caused; the grinding chips are not easily separated, the grinding force increases during the grinding process, and then workpieces undergo local burn and deformation [3]. It has been verified that the belt grinding technology is a good method for significantly improving the titanium alloy grinding efficiency and surface quality with good consistency [4]. However, there are many influencing factors on the precision manufacture of belt grinding, including the grinding motion, external grinding condition, contact condition and parameters of belt grinding, grinding planning, and characteristics of the belt and contact wheel; in addition, actor variables are affected by each other [5–9]. The profile precision and surface quality of key titanium alloy components for aerospace/energy applications would be seriously affected if there were not a titanium material removal model and functional mechanism with the above influencing factors in belt finishing.

There have been many research studies on belt finishing technology and its application. Mansori et al. [10–14] investigated their effects on the surface finish and on the form aspects in connection with the principal physical mechanisms activated during the belt finishing operations, conducted a study to achieve precision belt grinding based on identification of the prevailing relationships between the changing features of fixed grains on flexible coated belts and grinding performance, and introduced a multi-

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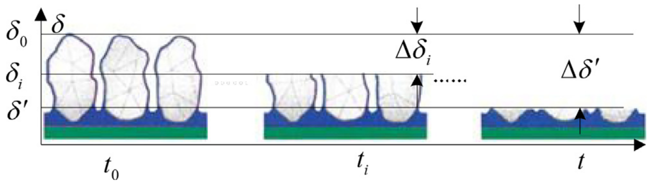

Fig. 1. Grain wear rule of normal belt finishing.

scale decomposition method of the surface topography based on a continuous wavelet transform. Jourani et al. [15,16] used a 3D model with multi-asperity abrasive wear on real-world rough surfaces to study the contact between a belt made of abrasive grains and the surface and influence of abrasive grain geometry on the friction coefficient and wear rate. Rech et al. [17] provided a comprehensive characterization of partial residual stresses produced in dry turning of a hardened AISI52100 bearing steel using PCBN tools, as well as its modification after a special abrasive finishing operation, i.e., belt finishing. Huang et al. [18–20] systematically studied the technology of follow finishing crankshaft journals with a belt, including the belt finishing mechanism and finishing motion equation, finishing error compensation and detection technology, and so on. Xiao et al. [21] illustrated a new belt finishing method for improving the PF-precision (profile accuracy and surface quality) of the blisk, and the results show that the surface roughness is less than 0.25 μm, the profile accuracy is less than 0.05 mm, and the PF-precision consistency is significantly improved.

From the above analysis, the surface quality and profile precision would be significantly improved with the method of traditional belt finishing. However, it is usually used for the polishing of crankshafts, camshafts, shaft-necks and so on; due to the limitations of its structure, the grinding mechanism makes it difficult to precisely control the material removal. Therefore, it is necessary to propose a new belt efficient finishing method.

Researching the material removal of belt grinding, Axinte et al. [22] investigated the possibility of using belt polishing as a final finishing operation for components made of Ti-6-4 heat-resistant alloy; the attempt consists of achieving a required workpiece surface quality/integrity that ensures high fatigue performances of the polished components. Huang et al. [23] analysed the material removal mechanism of belt grinding with the influence of belt speed, feed speed and grinding pressure for titanium material, and the optimal parameters of belt grinding for titanium alloy are obtained after the orthogonal experiment. Wang et al. [24] proposed a surface removal contour (SRC) model for grinding the complex surface of a blade; as a result, the surface roughness was more than 17.5% over the processing requirement and beyond a 30% maximum error, exceeding the standard. Zhu et al. [25] introduced a microscopic-scale ploughing force model, and characterisation of cutting mechanisms generated by robot-assisted belt grinding of titanium alloys is provided from the energetic aspect based on experimental forces. Unyanin et al. [26] proposed a formula for calculating the force pressing the abrasive belt to the grinding wheel in cleaning, and for comparison, experimental results are presented.

The literature referenced above reveals that current research on the material removal of belt finishing mainly focuses on qualitative analysis, and the material removal of belt finishing is difficult to predict, so the application of belt grinding technology in the precision machining of complex surfaces of titanium materials would be seriously affected. Additionally, the material removal model of belt finishing for precision manufacturing has not been investigated.

This paper aims to establish a model of life-cycle material removal (LCMR) for a newly proposed method of BEF (belt efficient finishing). And then, the final precision finishing operation for components made of titanium alloy isrealized. To realize that, firstly, the theory model of LCMR is established by the curvature of LCMR for BEF, which is based on the material removal mechanism of normal belt finishing. Secondly, the parametric mathematical models of LCMR for BEF, which is used for titanium alloy materials with flat and cylindrical surfaces, are established by the method of least squares multiple linear regression analysis, after orthogonal experimentation. And then the F-test method is used to verify the significance of the model. Finally, the material removal of the BEF mechanism is analysed for different finishing parameters, conditions and movements with the single factor experiment method, and the parametric mathematical models of LCMR for BEF are simultaneously verified.

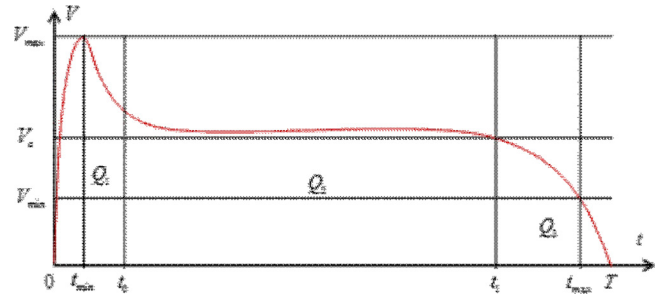

Fig. 2. Material removal curve of belt finishing.

2. Theoretical material removal model for LCMR in BEF

2.1. Rule curve of material removal

The material removal can be calculated quantitatively via the geometry of the workpiece and the tool during the traditional metal-cutting process. However, it is difficult to accurately calculate the material removal in the belt finishing process, which is due to the uneven distribution of the abrasive belt grain, the grain size not being consistent, elastic contact, the cutting angle of the grain becoming larger, and so on.

As shown in Fig. 1, the belt grain wear thickness is $\Delta\delta_i$, the grain height is reduced from δ_0 to δ' after the belt finishing time t, and then the grain wear of belt finishing continues changing during the grinding operation; the entire grain wear thickness is $\Delta\delta'$ [21].

The typical characteristic curve of LCMR in belt finishing is shown in Fig. 2, which was obtained from an earlier study of belt finishing material removal characteristics for the typical material.

As shown in Fig. 2, T is the belt finishing cycle, $t_{\min}$ is the maximum material removal time, $t_{\max}$ is the minimum material removal time, t_0 is the start time of stable material removal, and t_1 is the stop time of stable material removal. To accurately assess the characteristics, set the effective finishing time $t_E = t_{\max}$-t_{mmin} and the stable finishing time $t_S = t_1$-t_0.

As shown in Fig. 2, the belt finishing material removal curve is similar to the normal distribution curve when the grinding time is between 0 and t_0; this is mainly due to the uneven distribution and sharp abrasive grain at the beginning of belt grinding; the highest material removal point occurs at time $t_{\min}$, and the total amount of material removal is Q_1 at this stage. The stabilized period of belt grinding is when the belt grinding time is between t_0 and t_1. This is not only the engineering application stage but also the currently predictable stage. At this stage, the total amount of material removal is Q_2. The rapid wear period of belt grinding is when the belt grinding time is between t_1 and T. This stage is similar to a parabola; when the time reaches $t_{\max}$, the surface roughness of the belt finishing increases dramatically. At this stage, the total amount of material removal is Q_3.