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Overview on Abrasive Belt Grinding for Complex Surface

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Abstract—**Abrasive belt grinding technology is an important part of the precision forming process of complex profile parts. Based on the planning of grinding path, contact model and material removal model, the research and application progress of abrasive belt grinding technology at home and abroad are summarized, and the problems and research directions in the research of complex profile abrasive belt grinding technology are pointed out.**

Keywords-Abrasive Belt Grinding; Complex Surface

I. PREFACE

In recent years, with the continuous breakthrough and progress in the aerospace, shipbuilding and vehicle industries at home and abroad, the complex profile parts represented by the blade structure have been more and more widely used. As a new grinding technology, abrasive belt grinding has the characteristics of low grinding temperature and high grinding efficiency, and has been widely used in precision grinding of complex surface parts. Grinding is usually the last step in the processing of complex profile parts. The machining accuracy and surface quality of such parts will be the key factors that ultimately determine the performance of the equipment. However, belt grinding is different from conventional milling and wheel grinding. Abrasive belt grinding is achieved by rubber wheel contact, which results in uneven pressure distribution on the workpiece contact surface and large deformation in the normal direction. The mathematical correlation between material removal and feed rate is extremely complicated[1-2]. This requires further exploration and research on the planning of the abrasive belt grinding path and the establishment of the contact model and material removal model.

II. ROUTE PLANNING FOR ABRASIVE BELT GRINDING OF COMPLEX PROFIL

Reasonable machining path is an important guarantee to improve the efficiency of grinding and machining accuracy. It is usually considered from the aspects of line spacing and pass length. A lot of research has been done on the path planning of rigid machining systems, but there are few studies on the path planning of grinding of complex profile belts.

S. Mansour has studied the automatic programming of milling of free-form surface parts, and developed a software system for automatic generation of free-form surface CNC milling tracks based on IGES format or other CAD software models[3]; R. Sarma et al. studied the generation of tool path in NC grinding. A method of generating tool path considering manufacture and measurement was proposed. The experimental results show that the method can improve the surface quality of surface processing and make the prediction of surface roughness possible before processing[4]; Stephen P. Radzevich studied the tool path generation method for multi-axis NC machining of free-form surface, and proposed the concept of minimum time tool path, and discussed the problem of local and global tool path trajectory generation[5].

Duan Jihao et al. finished the flexible polishing process of engine blades through the research of polishing path planning technology. When the blade is polished by the abrasive belt contact wheel, the contact wheel and the blade are in line contact, and the free surface of the blade is approximated by the ruled surface fitting.

According to the width d of the abrasive belt contact wheel, n dividing lines are inserted into the XZ plane. M and N points are inserted on the i and i+1 partitioning lines respectively, and n lines are connected to point n_i by m_i of each point on the i partitioning line with larger curvature. By comparing the errors between the line segment and the blade, the fitting line segment $m_i n$ at the fixed point m is obtained, and the fitting line group mn is obtained. Then the blade fitting ruled surface is obtained by sweeping the curve. According to the radius r of the contact wheel, the equidistant ruled surface is determined. The polishing program of ruled surface is programmed by Unigraphics, and the blade profile polishing is realized. The process is shown in Figure 1.

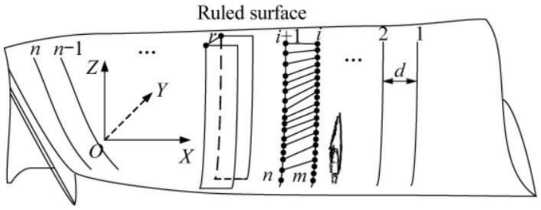

Figure 1. Ruled tool path and programming method

Lin Xiaojun put forward the concept of effective fit between contact wheel and blade profile, and realized effective fit between abrasive belt and blade profile by improving polishing tools, adopting flexible polishing technology and controlling polishing axis vector. As shown in Figure 2. Processing experiments were carried out on a five-axis CNC abrasive belt grinder. After polishing, the roughness reaches 0.25-0.39 μm, the profile of the blade changes 0.007 mm before and after polishing, and the polishing removal amount is between 10-16 μm. Good processing results have been achieved.

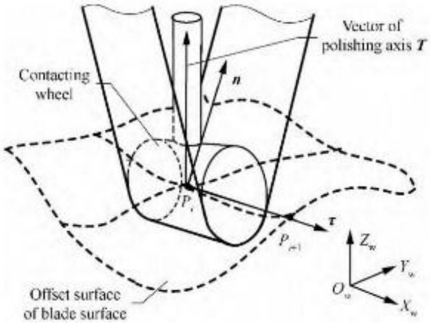

Figure 2. Contacting wheel posture under effective matching

According to the characteristics of the rubber contact wheel structure and the blade profile, Li Daqi divides the machining surface into three processing areas[8]. Based on the analysis of the relationship between the material removal amount and the travel line spacing, the travel line spacing is optimized. The grinding process uses the optimized combination of grinding parameters. The surface roughness of the blade after grinding and polishing can reach 0.735μm, which improves the processing efficiency.

Yang Yuhang proposed a method to generate the step size of "getting next point by former one". This method first obtains the surface geometric information of the knife contact and calculates a reasonable step value according to a certain rule, and then uses the value as a radius to make an arc, and the intersection of the arc and the profile is the next knife contact. This method can choose the corresponding step size calculation method according to the curvature of the profile surface, and it has strong adaptability

At present, the thought and basic method of path planning for abrasive belt grinding are the same as that of rigid grinding system. However, due to the deformation of contact force between rubber contact wheel and workpiece in the process of grinding, there are obvious differences between theoretical and actual removal amount, and the expected precision requirements cannot be obtained efficiently[10-11]. Although the CNC belt grinding based on the path planning of the rigid machining system can meet the final machining requirements, it is still impossible to achieve precise grinding of complex profiles.

III. CONTACT MODEL OF ABRASIVE BELT GRINDING

Since the belt pulley of the belt machine is a rubber wheel, the belt grinding system is a flexible system. During the grinding, the rubber wheel is elastically deformed by contact with the workpiece, so that the grinding contact point becomes the contact surface. This creates two problems that are difficult to control. On the one hand, the amount of material removed is much smaller than the feed due to the elastic deformation. On the other hand, it is difficult to accurately calculate and measure the pressure distribution on the contact surface because of the change from point contact to surface contact[12]. In the past research practice, the pressure distribution of the contact area was usually calculated by the Hertz contact theory and the finite element method.

A. *Hertz elastic contact theory*

The contact between rubber contact wheel and machined surface is not point contact, which is usually called surface contact. When grinding, the direction of grinding force is tangent perpendicular to the profile. Zhang Lei et al. constructively proposed the concept of surface removal profile when describing the removal of grinding materials for complex profile abrasive belts[13-14]. In their research, the contact between the rubber contact wheel and the workpiece profile is in accordance with Hertz's elastic contact theory. The contact pressure is obeyed by an elliptical Hertz distribution and the contact area is elliptical. On the premise of this assumption, taking the polishing of cylindrical surface by cylindrical grinding head as an example, the modeling method of surface removal profile is discussed emphatically. The direction of the grinding track is the axial direction of the cylindrical surface, where the contact between the two is a typical elliptical contact. Figure 3 shows the elliptical contact area. Y direction is the direction of polishing trajectory, *a* and *b* are the length of long and short half axes of contact ellipse.

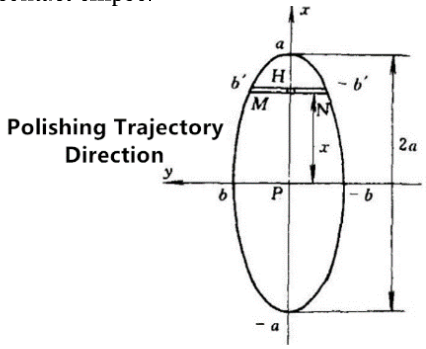

Figure 3. Contact ellipse

The contact surface between the contact wheel and the workpiece surface is elliptical[15-16]. The long half-axis is *a* and the short half-axis is *b*. The semi-ellipsoidal distribution of the pressure in the contact area is expressed as:

$$p(x,y) = -p_0\sqrt{1-(\frac{x}{a})^2-(\frac{y}{b})^2}\ . \tag{1}$$

In the formula, p_0 is the maximum pressure at the center of the contact area.

B. Finite Element Method

In abrasive belt grinding of metal materials, rubber contact wheels can be regarded as elastomers. The elastomer is divided into a large number of element meshes according to the rules by finite element method, and the material properties of the meshes are given at the same time. The model is used to solve the contact pressure value by means of the minimum energy method and the force balance equation[17-18]. Figure 4 is a classical state of contact between a rigid body and an elastic body.

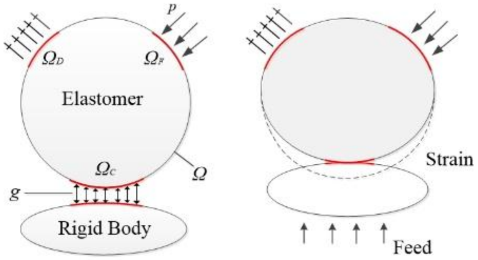

Figure 4. Signorini contact model

In the figure, Ω is an elastic body, and Ω_F is an action surface of the external force *P*; Ω_D is the fixed surface of elastomer, it cannot move and its deformation is zero; Ω_C is the contact area; *g* is the spacing between the rigid body and the elastomer.

Zhang developed a new model based on Support Vector Regression (SVR) technology to replace the FEM model to calculate the force distribution[19]. The new model approximates the FEM model with an error of less than 5%, but the execution speed is faster. The model they built is not only a simple physical model, but also the selection of training data in the effective data, so as to optimize and solve the relevant parameters. This new model based on support vector regression technology can not only simulate in real time, but also control the on-line robot in the grinding process.

Scholars such as Blum and Suttmeier[20] used the force balance equation and the minimum energy method to establish a finite element model. The model sees the contact between the contact wheel and the workpiece as a Signorini contact problem. They have carried out relevant research work on quantitative grinding under flexible contact condition, and preliminarily obtained the mathematical model of quantitative grinding of abrasive belt. Their research shows that quantitative material removal by abrasive belt grinding is feasible.

At present, the established model of contact pressure distribution in abrasive belt grinding has great limitations. Although the Hertz elastic contact theory basically solves the problem of elastic contact of curved surfaces, the model established by this theory has not yet obtained the applicable range of abrasive belt grinding. The model established by the finite element method is solved by dividing the elements. Abrasive belt grinding is a process of using a large number of abrasives to work on the workpiece. If all the abrasives are discretized, a very large and complex model will be established, which is not conducive to the solution of the model.

IV. ABRASIVE BELT GRINDING MATERIAL REMOVAL MODEL

Establishing a reasonable material removal model is helpful to improve the removal efficiency and processing quality. Abrasive belt grinding is a very complex process. The parameters such as belt line speed, feed speed and grinding pressure are the key factors affecting the grinding performance[21-22].

A. Linear material removal model

The influence factors of abrasive sharpness, abrasive size and material type are simplified to K_p . The removal efficiency of a single abrasive material in the Preston equation is directly proportional to the pressure and linear velocity it receives. However, since there is not a single abrasive grain during the grinding process, and many abrasive belt abrasive particles have great differences in the ability of material removal, the Preston equation needs to be corrected according to the process parameters[23].

$$\Delta z = \int_0^t K_P \cdot v \cdot p dt \tag{2}$$

In the above formula, Δz represents the amount of material removal; *v* represents the relative velocity of movement of the abrasive particles; and *p* represents the relative pressure experienced by the abrasive particles.

Ji Shiming et al. introduced the ratio of the hardness of the workpiece to the hardness of the abrasive grains into the Preston equation to correct the Preston equation[24]. Zhang Lei et al. believe that the surface of the abrasive grain rubbed on the workpiece conforms to the tribological Archard equation, that is, when a wear-free abrasive grain slides on the surface of a relatively soft workpiece, the material removal volume *W* and the abrasive grain are applied to the surface of the softer workpiece. The grinding pressure *F* is proportional to the sliding distance L_s of the abrasive particles on the surface of the workpiece and inversely proportional to the hardness *HV* of the workpiece surface. The model of material removal volume based on Archard equation[25] is as follows:

$$W = k_{abr} \frac{F \cdot L_s}{HV} \, . \tag{3}$$

In formula k_{abr} is the wear coefficient.

The above two material removal models are linear in nature and have certain rationality. However, most of the contact between the abrasive particles and the workpiece during the grinding process is elastic deformation, and only a small part of the abrasive particles are plastically deformed in contact with the workpiece, which makes the model not fully applicable to practice. In addition, the model cannot be generalized for different grinding materials. Therefore, more parameters need to be introduced to build the model. Hammann believes that the instantaneous material removal rate of the material is a function of the parameters of the belt line speed, feed rate and contact pressure. He uses the Preston equation to propose a linear empirical formula[26]:

$$r = C_A \cdot K_A \cdot K_t \cdot \frac{V_s}{V_w \cdot L_w} \cdot F_A \, . \tag{4}$$

In the formula above, r is the instantaneous grinding removal of material, C_A is the correction constant of grinding process, K_A is the resistance coefficient determined by abrasive and removed material, K_t is the durability coefficient of abrasive belt, V_s is the linear speed of abrasive belt, V_w is the feed speed of workpiece, L_w is the width of grinding area, F_A is the normal contact pressure acting on workpiece. According to this model, in addition to the normal contact pressure F_A , other parameters can be regarded as constant and can be obtained through a series of experimental data.

B. *Nonlinear material removal model*

Through a large number of experiments, the linear material removal model deviates greatly from the experimental results. Some researchers believe that the material removal rate is exponentially related to the parameters such as the belt line speed, feed rate and contact pressure. Cabaravdic proposed a model for removing local non-linear material in abrasive belt grinding[27]:

$$r = C_g \cdot V_b^{e_1} \cdot V_w^{e_2} \cdot F^{e_3} \, . \tag{5}$$

$C_g = C_A \cdot K_a \cdot K_t$, C_A is the correction constant of the grinding process, K_a is the resistance coefficient determined by the abrasive and the material to be removed, K_t is the durability coefficient of the abrasive belt, V_s is the linear velocity of the abrasive belt, and F is the normal contact pressure of the grinding point, e_1、e_2 and e_3 are constants. This model describes the local material removal efficiency in the contact surface, where the parameter of the grinding area width has no meaning for the Hammann model. The width of grinding zone can be regressed by the experimental data of abrasive belt grinding with uniform pressure distribution on the contact surface, and the correction coefficient C_g and the coefficient e_i of grinding parameters can be determined.

At present, abrasive belt grinding can basically meet the final requirements, but it is still difficult to achieve efficient and accurate material removal. In the existing research on material removal in linear and non-linear abrasive belt grinding, only plane workpiece is taken as the object of study. Further research and in-depth theoretical analysis are needed to establish an accurate material removal model for constant pressure abrasive belt grinding.

V. SUMMARY

In recent years, with the advancement and development of various technologies, the abrasive belt grinding technology has partially replaced the manual grinding and polishing and optimized the machining precision under the combination of other technologies. Mainly reflected in the numerical control of abrasive belt grinding equipment, CNC equipment has obvious advantages for complex surface precision machining. Combined with automated production line, it will be the inevitable trend of mass production of blade parts. The abrasive belt grinding technology is intelligent. With the rapid development of artificial intelligence and its continuous integration with traditional manufacturing technology, the intelligent level of grinding technology will be gradually improved, such as grinding force self-feedback, tool path optimization, grinding process parameter simulation. Intelligentization will play a significant role in exploring the abrasive belt grinding mechanism and improving the quality and efficiency of grinding.

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