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Polishing Path Planning of Complex Curved Surfaces and the Realization of Automatic Control

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Abstract

Polishing technology is a final surface finishing process. The main aim is the removal of the machining marks to make the surface bright and clean. Polishing is often difficult to realize automatic mechanical polishing due to the polishing quality requirements and workpiece shape. Aiming at the problem, an automatic polishing technology has been proposed. In the paper, a new polishing path determining a method has been proposed. With this path, the abrasive properties have been studied. Firstly, the abrasive has been selected according to the surface roughness experiment; then, the detailed parameters of processing have been researched. The experimental results show that there is a reasonable grain size meeting the roughness requirement of the workpiece surface with relatively larger abrasive grain size. Besides, it can also be concluded that the roughness of the workpiece surface and the path planning of the abrasive and the processing parameters have high relationship, and only the full consideration of all the parameters can help to improve the processing efficiency with the low cost.

Keywords*: polishing path, complex curved surfaces, automatic control, black silicon carbide*

1. Introduction

Polishing technology [1-3], which is also known as mirror machining, is a final surface finishing process for the inside and outside surface of the parts with a fine abrasive [4-5] and soft tool. The main aim is the removal of the machining marks, including pits, burr, and so on. With this process, the surface will be bright and clean. Usually, polishing is performed on the workpiece surface for a small amount of grinding, and the impact on the shape and size of the workpiece is quite small. The Polishing not only can beautify the appearance of the workpiece, but also can improve the surface wear and corrosion resistance of the workpiece and get some special performance. Polishing can be used as both the last work process and surface pretreatment of the workpiece coating.

The polishing process are mainly applied in precision machinery [6], electronic equipment [7], instrumentation [8], medical equipment and household appliances, kitchen utensils, *etc*. The polishing quality greatly affects the quality of the product, and selection of the appropriate polishing process and the method is quite important to improve the quality of the products. The main method of the stainless steel polishing methods [9-14] are manual polishing, mechanical polishing, electrochemical polishing, ultrasonic polishing, polishing fluid and magnetic polishing, *etc*., as shown in Table 1.

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Table 1. The Main Types of the Polishing Methods

	Types		
Polishing process	Mechanical method [15-16]	Non free abrasive tool	Abrasive belt polishing; elastic wheel polishing; power brush polishing; finishing grinding
		Free abrasive tool	Rolling mill; magnetic abrasive; squeeze grinding; liquid vapor jet; shot peening
	Chemical and electrochemical methods [17-18]	Electrochemical vibration polishing; electrochemical polishing; electrolytic grinding; ultrasonic processing	
	Heat effect [19]	Heat resistance wire process; high temperature to burr	

Polishing is one of the most important processes in the production of stainless steel. It is a difficult problem to realize automatic mechanical polishing. There are several technical difficulties: (1) Polishing quality requirements are relatively high, and the processing surface requires material removal uniformity with no deformation and polishing lines. Meanwhile, the workpiece, which is difficult clamping material, is the thin material. Therefore, it will be easy to produce deformation and the hardening phenomenon of the workpiece during the polishing process. (2) The shape of the workpiece is often complex and surface is often with some special structure and it is difficult to achieve automatic polishing trajectory. Meanwhile, it also restricts the efficiency of polishing;

The purpose of this research is to develop an automatic polishing technology [20], which can be economically and practically applied in the stainless steel products. A set of polishing process is developed, which is suitable for the automatic mechanical polishing of stainless steel, and the path is planned to improve the polishing quality and efficiency. The main contribution of this paper is developing a new polishing path. The remainder of the paper is organized as follows: The new polishing method is given in Section 2. Verification is shown in Section 3, and the conclusion is shown in Section 4.

2. A New Polishing Method

In the new polishing method, cutting tool path planning is the main subject.

2.1 The Basic Cutting Tool Path Planning Method

In the process of free surface polishing, the polishing tool path directly affects the polishing quality and the machining efficiency. Good machining path should improve the processing efficiency in the premise of meeting the requirement of processing accuracy. In numerical control machining, we should choose the right tool path according to the surface of the workpiece. At present, in the numerical control processing, tool path planning methods can be listed as [21-23]:

1) Ring cutting tool path. In this method, the contour curve is firstly found, equidistant line, which can be formatted by translating inside a tool radius, is adopted as the tool path. In the circular path planning method, the contour curve needs to be translated many times, and the calculation method is quite complex. It is commonly used in rough machining, and it efficiency is related low when it is used in the complex surfaces.

2) Parallel cutting plane method. With a set of parallel planes intercepting the surface, the obtained stub is used as the tool path. This method can make the tool path distribute more uniform, which is suitable for numerical control programming for complex surface.

However, this method is usually difficult to determine the best position of cutting plane, and the computation complexity is high. In general, the residual height along the tool path is often different, and the distance between the parallel planes can be determined by the maximum residual height.

3) Polyhedral tool path planning method. Under certain machining accuracy, the cutter location is obtained by using the polyhedral approximation of the surface of the workpiece, and the cutting tool is set on the surface of the workpiece to calculate the tool path. This method can be used for the tool path planning described by the triangular domain and scattered data.

4) Isoparametric line method. This method is a most important tool path planning method. The tool path is arranged along the parameter line of curved surface of the workpiece, and the cutter location data is obtained on the surface or the offset surface. The algorithm is simple and with higher computing speed. The disadvantage of the method is the spacing parameter can be determined according to the maximum residual height, while most of the workpiece surface parameter line distributed uneven. This will lead to the large difference of the actual tool path line density and reduce the surface machining quality and efficiency.

5) Iso-scallop Method. In this method, scallop height is used to control the distance between adjacent tool path, and next path of the machining tool is calculated by numerical iteration when calculating the current path. Scallop height produced by the tool along the path generated by the method will keep the same.

The tool path planning method should meet both the machining accuracy and high processing efficiency. The tool path planning method should follow the following principles:

1) Shorten the cutting tool path length. The higher processing efficiency will be obtained when the path length is shortened.

2) Continuity of the tool path should be good. The tool path should be as long as possible in order to avoid the time increase on the adjusting of the cutting tool position, which will decrease the machining quality and efficiency.

3) Keep the tool path consistent. Reducing the tool trajectory curvature can avoid the tool movement speed which affects surface quality and efficiency.

2.2 The New Cutting Tool Path Planning Method

A space path of the abrasive can be defined as a set of points passed by the abrasive. In the design process, the desired space path of the abrasive should be determined. When the path and the polishing direction have been considered, the problem can be transformed into the optimal time sequence. Then, the number of optimal variables in the general abrasive trajectory optimization problem will be reduced in the trajectory optimization problem. In order to guarantee the polishing depth in the area, it is quite important to optimize the v and track spacing δ.

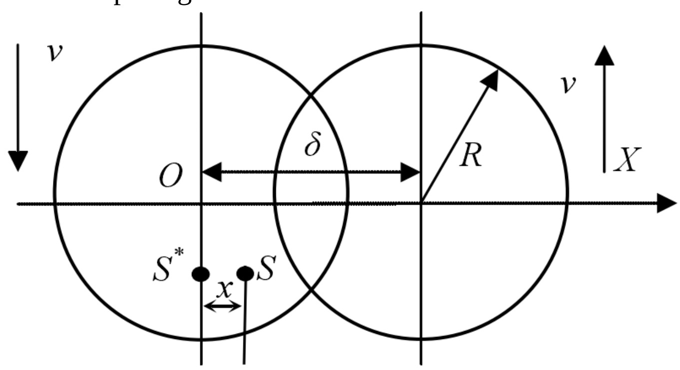

Figure 1. Schematic Diagram of Plane Polishing

Figure 1 shows a polishing process on a flat surface. x represents the distance between point S to the first path in a polishing radius; S^* is the projection on the polishing path; the point O is the projection point of the polishing tool. The polishing depth at point S is:

$$T_s(x) = \begin{cases} T_1(x) & 0 \le x \le \delta - R \\ T_1(x) + \lambda \cdot T_2(x) & \delta - R \le x \le R \\ T_2(x) & R \le x \le \delta \end{cases} \tag{1}$$

$$T_1(x) = 2\int_0^{t_1} f(r_1)dt \qquad 0 \le x \le R \tag{2}$$

$$T_2(x) = 2\int_0^{t_2} f(r_2)dt \qquad \delta - R \le x \le \delta \tag{3}$$

Where,

$$t_1 = \sqrt{R^2 - x^2} / v \tag{4}$$

$$r_1 = \sqrt{(vt)^2 - x^2} \tag{5}$$

$$t_2 = \sqrt{R^2 - (\delta - x)^2} / v \tag{6}$$

$$r_2 = \sqrt{(vt)^2 + (\delta - x)^2} \tag{7}$$

T_1 (x) and T_2 (x) represent the polishing thickness of points S of two adjacent paths; t_1 and t_2 indicates the distance of projection points on the center of abrasive on two adjacent; t is the time from point O moving to point S^*; λ is the overlapping factor of two adjacent path.

The polishing area of the workpiece surface in unit time is

$$Ts(x,\delta,v) = \frac{1}{v} J(x,\delta) \tag{8}$$

Where J is a function of x and δ. In order to make the uniform thickness of the polishing region, the minimum variance of the actual polishing thickness and the polishing thickness S is the optimal objective function:

$$\min E(v,\delta) = \int_0^{\delta} (T_s(x,\delta,v) - T_d)^2 dx \tag{9}$$

Where, T_d is the ideal polishing thickness which has been removed.

The method to calculate v and δ can be summarized as the following:

1) Set the initial value of δ_1, δ_2, ε;

2) Calculate v_1, v_2, E_1, E_2;

3) Calculate the value of δ_3, δ_4 according to the Golden section method;

4) Calculate v_3, v_4, E_3, E_4;

5) If E3≥E4, then, set $\delta_1 = \delta_3$, $E_1 = E_3$, and then the next step is processed. Or else, $\delta_2 = \delta_4$, $E_2 = E_4$, and then the next step is processed.

6) If $|\delta_1 - \delta_3| \le \varepsilon$, then the program stops, or else, go to the third step.

And the main steps of δ calculation method is:

1) Set the working space: $[a \quad b]=[R \quad 2R]$;

2) Set $\lambda = b-\tau(b-a)$, $\mu = a+\tau(b-a)$. calculate $\varphi(\lambda)$ and $\varphi(\mu)$;

3) If $\varphi(\lambda) < \varphi(\mu)$, then $b=\mu$, or else, set $a=\lambda$, and go to step 5);

4) If $b-a<\varepsilon$, $\lambda' = \frac{a+b}{2}$, the calculation will be cancelled, or else, set $\mu=\lambda$, $\varphi(\lambda)=\varphi(\mu)$, $\lambda = b-\tau(b-a)$, and, $\varphi(\lambda)$ should be calculated. Then, go to step 3);

5) If $b-a<\varepsilon$, $\mu = \frac{a+b}{2}$, the calculation will be cancelled, or else, set $\lambda=\mu$, $\varphi(\lambda)=\varphi(\mu)$, $\mu = b+\tau(b-a)$, and, $\varphi(\mu)$ should be calculated. Then, go to step 3);

3. Verification

3.1. Polishing Process

The properties of abrasive will affect the polishing and processing range. The automatic polishing process requires the stable and uniform properties of abrasive. Meanwhile, appropriate abrasive should be selected according to the characteristics of the workpiece material, polishing performance and the characteristics of machining. In general, high tensile strength of the workpiece is usually polished by larger corundum abrasives, while the workpiece with lower tensile strength is usually polished by silicon carbide with high brittleness and hardness. The hardness of the abrasive selected increases with that of workpiece increases. The characteristics of common abrasives are shown in Table. 2.

Table 2. Characteristics of Common Abrasives

Abrasive	Main characteristics	Field of application
Brown fused alumina	High toughness, strong resistance to crushing, wear resistance and high temperature resistance	Suitable for the processing of high tensile strength metal
White fused alumina	High hardness, low toughness, good cutting performance and self-sharpness	Suitable for processing heat resistant alloy steel and titanium alloy, *etc*.
fused alumina zirconia	High toughness, brittle, easily broken	Suitable for processing high hardness materials, such as steel, high carbon steel, high carbon steel, *etc*.
Black silicon carbide	High toughness, brittle, easily broken	Suitable for high toughness and low tensile strength.
Green silicon carbide	High hardness and toughness	Suitable for hard and brittle materials

3.2. The Polishing Experiment

By comparing the processing properties of abrasive, white fused alumina, fused alumina zirconia and black silicon carbide with the same particle size are selected for the processing of steel. A workpiece with complex curved surface is adopted as the polishing object. The surface rough degree is used as criteria to verify the polishing performance. In the experiment, polishing wax is used as the polishing agent. The abrasive peripheral speed is 12.5~32.5 m/s, and the feed rate is 0.15~0.25 m/min. Polishing pressure is 20±1 N.

Curve of surface roughness with the line speed of the polishing wheel is described in Figure. 2. It can be seen that surface roughness of the workpiece is the smallest when black silicon carbide is selected as the abrasive, which means the material removing from the processing surface is uniform. In the results, there is no burning on the surface and polished grain is very delicate. When the grain size is larger, the grain size will be coarse and scratches will be easily produced on the surface of the workpiece. When the size is small, the material will be removed uneven from the surface, and the surface roughness becomes big. Then, it is difficult to control the polishing pressure, polishing time and other processing conditions.

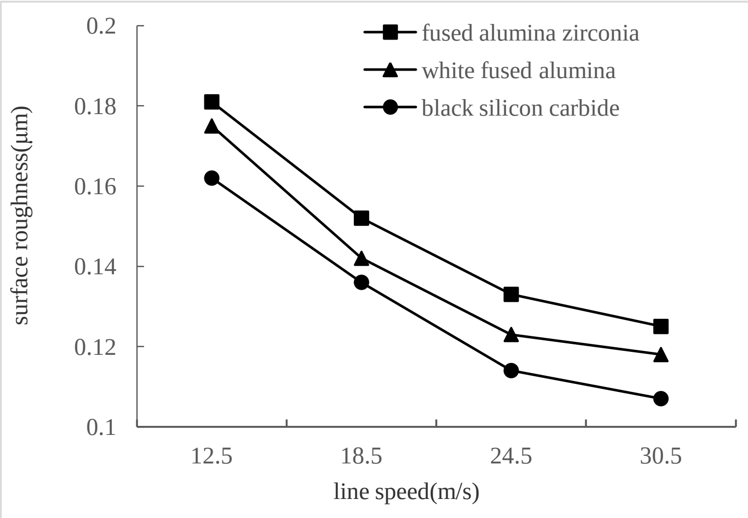

Figure 2. Curve of Surface Roughness with the Line Speed

3.3. Effect of Grain Size on Polishing Performance

From the results in the Figure 2, black silicon carbide is selected as the abrasive in the further study. Under the same experimental conditions, experiment of different grain size of abrasive on the polishing performance has been proposed to determine the appropriate granularity of abrasive. Three kinds of grain size of P400, P600, and P1000 are selected. The polishing object is still the complex curved surface. Yellow polishing fault is used as the polishing agent. Peripheral speed ranges from 12.5 to 30.5, and the feed rate is 0.15~0.25 m/min while the polishing pressure is 20±1 N.

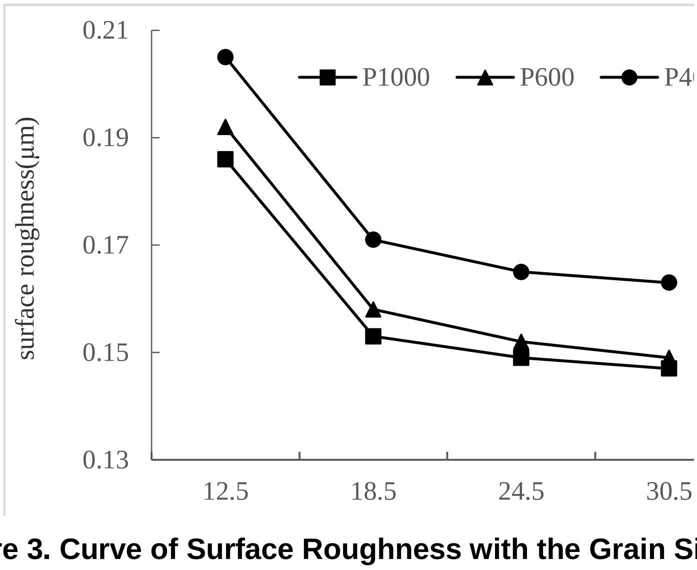

Figure 3. Curve of Surface Roughness with the Grain Size

Figure 3 shows the results of the experiment of the curve of surface roughness with the grain size. It can be seen some useful results: (1) with the P600 and P1000 grain size of abrasive, the surface roughness is small, and surface material removes uniformly. The polishing work is with high quality; (2) when the grain size decreases to a certain degree, the surface roughness of the workpiece minor changes. Therefore, there is a reasonable grain size meeting the roughness requirement of the workpiece surface with larger abrasive grain size. Further, it can be deduced that the roughness of the workpiece surface and the path planning of the abrasive and the processing parameters have a high relationship, and only the full consideration of all the parameters can help to improve the processing efficiency with the low cost.

4. Conclusion

The polishing not only can beautify the appearance of the workpiece, but also can improve the surface wear and corrosion resistance of the workpiece and get some special performance. Polishing is one of the most important processes in the production of stainless steel, which is often difficult to realize automatic mechanical polishing due to the polishing quality requirements and workpiece shape. Aiming at the problem, an automatic polishing technology has been proposed

In this paper, the properties of the abrasives are firstly given. By comparing the processing properties, some abrasive has been selected for the processing of steel. A workpiece with complex curved surface is adopted as the polishing object. According to the experiment, black silicon carbide can help to improve the surface quality. In the further study, black silicon carbide with different processing parameters are investigated. With three kinds of grain size, some useful results have been obtained: (1) with the P600 and P1000 grain size of abrasive, the surface roughness is small, and surface material removes uniformly. (2) when the grain size decreases to a certain degree, the surface roughness of the workpiece minor changes. Therefore, there is a reasonable grain size meeting the roughness requirement of the workpiece surface with larger abrasive grain size.

Besides, it can also be concluded that the roughness of the workpiece surface and the path planning of the abrasive and the processing parameters have high relationship, and only the full consideration of all the parameters can help to improve the processing efficiency with the low cost.

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