Research on Robot Grinding Technology Considering Removal Rate and Roughness

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Abstract. In order to solve the problem of poor consistency and low processing efficiency of artificial grinding, this paper establishes a six-axis robot automatic grinding platform. In the first section of the paper, the qualitative relationship between the process parameters and the grinding quality could be learned from the single factor experiment, and the primitive range of the process parameter domain is obtained. On the basis, an orthogonal experiment is carried out, and a quantitative regression empirical model is established. Then the parameter sensitivity function is deduced based on the model. In regards to the grinding quality and stability constraints, the process parameter domain optimization is carried out. Finally, considering the influence of grinding attitude, the optimal attitude angle is found in the range of process parameters. The results show that the blade grinding system and the grinding scheme are effective.

Keywords: Robot grinding system · Grinding quality · Grinding angle · Optimized parameters domain · Turbine blades

1 Introduction

Turbine blades are one of the key components of Aero-engine and have a very important impact on the performance of an engine. At present, the turbine blade grinding is mainly rely on manual, the product pass rate of current is low and the consistency is poor, which directly reduces the blade production efficiency. However the unique multi-joint structure of the robot and the high processing flexibility make it very suitable for the grinding of the complex surface of the blade. The robot grinding product has high consistency and high machining precision, which can greatly reduce the labor cost and improve the automatic production efficiency [1].

At present, the research on grinding is mainly focused on the process system research or process parameters optimization. Tsaai and Huang [2] optimized the abrasive grain size, polishing pressure, tool speed and feed rate in the robot grinding system, and analyzed the influence of each parameter on surface roughness and grinding efficiency. Song et al. [3] studied the relationship between the material removal rate of the robot belt grinding system and the workpiece curvature, contact force, robot speed and belt speed, and established a robot grinding adaptive model. Sabourin et al. [4] introduced a method for grinding a turbine blade by a robot. By adjusting the process

Y. Huang et al. (Eds.): ICIRA 2017, Part II, LNAI 10463, pp. 79–90, 2017.
DOI: 10.1007/978-3-319-65292-4_8

parameters, the surface roughness can be reduced to Ra = 0.1 μm. Ahn et al. [5] gives the formula for calculating the surface roughness, indicating that the surface roughness value is related to the tool speed, feed rate, grinding times and the thresholds that the abrasive can achieve. Tsai et al. [6] proposed a uniform material removal model for the constant force and constant speed grinding method. The results of experiments show that the method can reduce the third of the profile error.

In order to keep the grinding force constant, many scholars have done a lot of research. Pessoles and Tournier [7] proposed a 5-axis CNC grinding system based on grinding force and displacement control. Brecher et al. [8] developed a force control device and a control system for robot grinding. Pan and Zhang [9], aiming at the flexible grinding of industrial robots, created a grinding force control method has proven to obtain good surface quality.

Generally the existing force control system for the blade grinding process platform is complicated, and its control is relatively difficult and the scalability is also poor. Moreover, in current research, the parameters on the grinding process range are narrow and are mainly concerned with abrasive grain size, grinding force, grinding line speed and feed rate of four process parameters. The research about the influence of a grinding angle on a grinding surface quality is relatively limited.

In view of the above situation, this paper introduces the flexible adaptive force controller -ACF and constructs a flexible robot grinding system. Based on the system, the influence of process parameters including the attitude angle is analyzed and the optimization selection is observed. The first part introduces the composition of the flexible grinding system of the robot and the basic working principle of the flexible force controller; in the second part, the preliminary selection and optimization of process parameters are carried out, and the influence of grinding angle on grinding effect is analyzed, and the optimal parameters of grinding process and the optimal combination scheme are obtained. In the third part, the preliminary grinding experiments of the turbine blades are carried out, and the effectiveness of the flexible grinding system and the grinding scheme are verified by taking the surface roughness and the material removal rate as the consideration.

2 Robotic Flexible Grinding System

The flexible robotic grinding system is mainly built for the grinding process of the turbine blades. The blades are clamped on the special fixture of the table. The adaptive force controller and the grinding tool are connected to the end flange of the six-axis robot. Blade grinding is mainly done in the form of manual teaching or offline control. The main purpose is to make the material removal of the blade constant and to eliminate the milling lines in order to meet the requirements of surface accuracy and surface roughness. The main hardware of the grinding system consists of the robot body, the flexible force controller, the electric spindle, the grinding tool, the blade and the fixture as shown in Fig. 1.

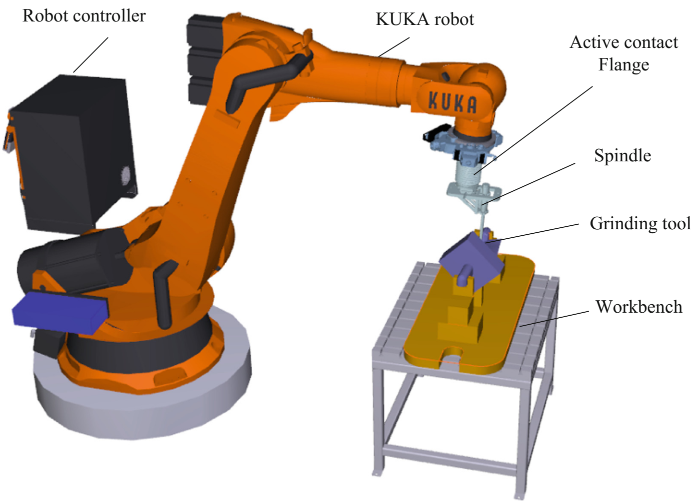


Fig. 1. The hardware of the robot grinding system

2.1 Robot Motion Control System

The robot motion control system consists of a KUKA KR210 robot body and robot control cabinet KRC2. The KUKA robot body is the main movement part of the grinding operation, which can be divided into three parts: 1. Robot base, which is used to fix the robot body; 2. The arms, which consist of six connecting rods by turning pairs; 3. Robot control cabinet, through which you can make the grinding tool to move in accordance with the program.

2.2 Adaptive Force Control System

Grinding force is a very important parameter in the grinding process, which has an important effect on the grinding quality and efficiency. Therefore, it is necessary to monitor and control the grinding force in the process accurately. This paper will introduce an adaptive force controller-ACF, which is a flange connected robot and grinding tool that can control the robot's end output to a constant force.

Flexible force control system first need to detect the grinding force, and then change the pressure from the proportional valve output to control the cylinder action, in order to achieve the adaptive compensation of the grinding movement. When a certain force is set, the amount of expansion and contraction of the ACF is detected, and the ACF control system controls the magnitude of the air pressure in the cylinder. The workflow is shown in the Figs. 2 and 3.

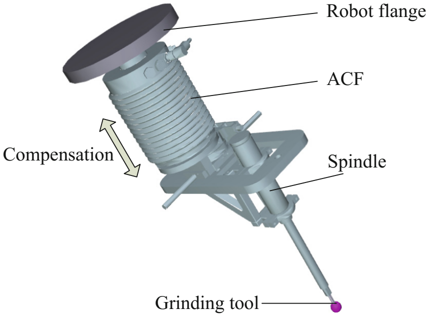


Fig. 2. The installation of the ACF

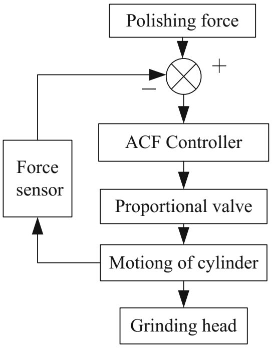


Fig. 3. The force control process of the ACF

2.3 Grinding Power System

The grinding power system consists of a high-speed spindle and a grinding tool that is held at the end of the motor spindle. The flexible force control system is installed at the end of the adaptive force controller to control the grinding speed and grinding force of the grinding tool. The most common grinding tools are rubber, leather, wool grinding heads, grinding wheels, sandpaper, etc. The base of a rubber grinding head generally uses a highly elastic material, which makes it flexible. Widely used in the field of aerospace, the rubber grinding head can properly compensate for the robot path error or bypass the processing error of the blade.

3 Robot Flexible Grinding Process

In order to study the relationship between the grinding process parameters and the surface quality of the blade, this section will discuss the selection of the appropriate abrasive and the initial process parameter field by single factor experiment. After that, the process parameters are selected in the grinding process parameter field for orthogonal experiment, and the measurement results and the grinding process parameters are analyzed by regression analysis. Then the sensitivity of the grinding process parameters has been analyzed, and the sensitive relationship between the surface removal rate, surface roughness and grinding parameters are obtained. The sensitivity of the process parameters is calculated by the sensitivity calculation of the sensitive process parameters, and the range of the sensitivity of the process parameters is obtained. Finally, the influence of the grinding attitude angle on grinding effect is analyzed by orthogonal experiment, and the validity of turbine blade is confirmed.

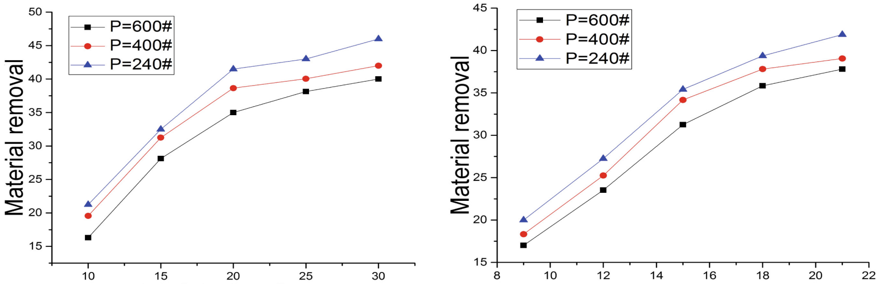
3.1 Grinding Power System

According to the experience manual and other papers [10, 11], the initial grinding process parameters range are robot feed rate Vw = 10–70 mm/s, grinding line speed Vs = 5–25 m/s, grinding force size Fn = 10–50 N.

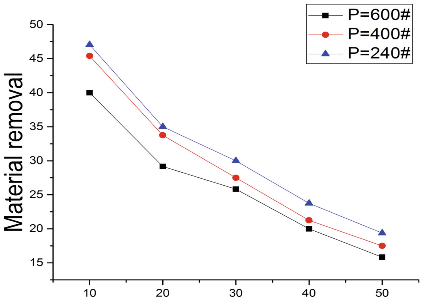
Abrasive selection is an important process in conducting experimental research. In general, it depends on the characteristics of the workpiece, including the shape of the workpiece, size and material grinding performance. TC11 titanium alloy is difficult to be processed, in the grinding process, and the grinding force is relatively large and grinding temperature is relatively high, potentially causing adhesion and chilling phenomenon. Therefore, this paper chooses the grinding tool of silicon carbide material, which has the characteristics of high hardness and good grinding performance. In order to verify the effect of different size grinding head on the processing effect, the selected particle size was 240 #, 400 # and 600 # respectively.

3.2 Primary Experiment of Grinding Abrasive Based on Single Factor Experiment

Figure 4 shows the influence of the grinding characteristics and the grinding process parameters on the surface removal depth of the material.



(a) Grinding force (b) Line speed

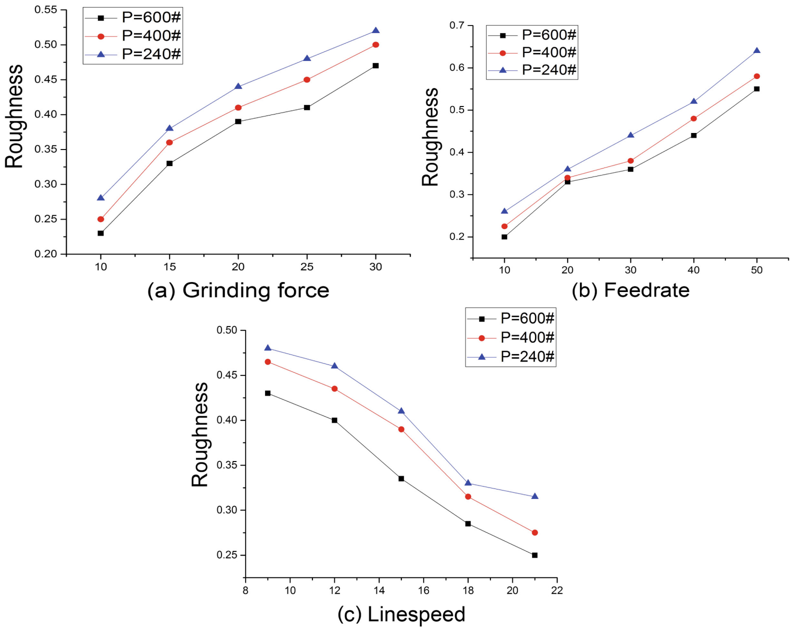


(c) Feed rate

Fig. 4. Effect of grinding characteristics and grinding process parameters on depth of material removal

Figure 4(a) shows that the maximum removal depth increases with the grinding pressure. Figure 4(b) shows that the maximum removal depth of the material is positively related to the line speed, that is, the faster the grinding line speed, the larger the material removal depth. Figure 4(c) shows that the maximum removal depth is inversely related to the feed rate of the grinding head. The greater the feed rate, the lower the maximum removal depth of the material.

Based on the comprehensive analysis of three graphs, it can be found that the higher the particle size of the grinding head, the lowest depth of material removal, and the depth of material removal is inversely related to the abrasive grain size. The reason is that when the abrasive grain size is higher, the abrasive grain distribution density is bigger. In the case of the same process parameters, abrasive cutting depth is small, and elastic deformation will occur without material removal, so the material removal depth is relatively small.



(a) Grinding force (b) Feedrate

(c) Linespeed

Fig. 5. Effect of grinding characteristics and grinding process parameters on surface roughness

Figure 5 shows the influence of grinding head characteristic parameters and grinding process parameters on grinding surface roughness. Figure 5(a) shows that the roughness and grinding force is positively correlated, that is, the greater the grinding force, the greater the surface roughness. Figure 5(b) shows that the roughness value is positively correlated with the feed rate of the grinding head, that is, the larger the feed rate is, the larger the surface roughness value is. As can be seen from Fig. 5(c), the roughness value is inversely related to the grinding line speed, that is, the larger the grinding line speed is, the smaller the surface roughness value is.

Based on these three images, compared with different grain size of the grinding head for the material surface roughness, it is convenient to find out that the higher the particle size of the grinding head is, the lower the surface roughness is. That means, the surface roughness of the material is inversely related to the abrasive grain size. The higher the abrasive grain size and the abrasive grain density is, the smaller the abrasive grain cutting depth in the same process parameters is. To sum up, considering the original definition of the surface roughness, it is easy to get the conclusion that the roughness value is relatively small.

The above-mentioned single factor experiments show that with the same grinding process parameters, the use of lower particle size of the grinding material paves the way to a higher depth of removal and a larger roughness. Taking into account the contour accuracy and roughness requirements of the blade shape, select the grinding tool with a particle size of 400 #. The initial range of other process parameters is: grinding head feed speed Vw = 10–40 mm/s, grinding head line speed Vs = 12–21 m/s, grinding force Fn = 10–30 N.

3.3 Effect of Grinding Process Parameters on Surface Quality Based on Orthogonal Experiment

In this section, the orthogonal experiment parameters are selected in the range of the grinding process parameters obtained by the single factor experiments, and the results of the measurement and the grinding process parameters are analyzed by regression analysis to establish the empirical formula of surface feature. Then, the sensitivity of the process parameters of the grinding surface is analyzed, and the sensitivity relation model between them is obtained. On this basis, the range of the sensitivity of the process parameters is obtained. These all support the optimization of the subsequent process parameter fields.

In order to establish the empirical formula, the multiple linear regression analysis method was used to fit the grinding process parameter data and the surface characteristic test data, and was established. As shown in Eq. (1)

$$\begin{aligned} R_a &= 0.4331 V_w^{0.273} F^{0.155} V_s^{-0.108} \\ H(0) &= 231.071 V_w^{-0.164} F^{0.173} V_s^{0.098} \end{aligned} \tag{1}$$

According to the surface characteristic data, the relative sensitivity of the process parameters is defined: the relative sensitivity is the exponential part of the exponential empirical formula. The relative sensitivity of the surface features to the grinding parameters can be calculated as Eq. (2):

$$\begin{aligned} S_{R_a}^{\prime V_w} = 0.273, S_{R_a}^{\prime F} = 0.155, S_{R_a}^{\prime V_s} = -0.108 \\ S_{H}^{\prime V_w} = -0.164, S_{H}^{\prime F} = 0.173, S_{H}^{\prime V_s} = 0.098 \end{aligned} \tag{2}$$

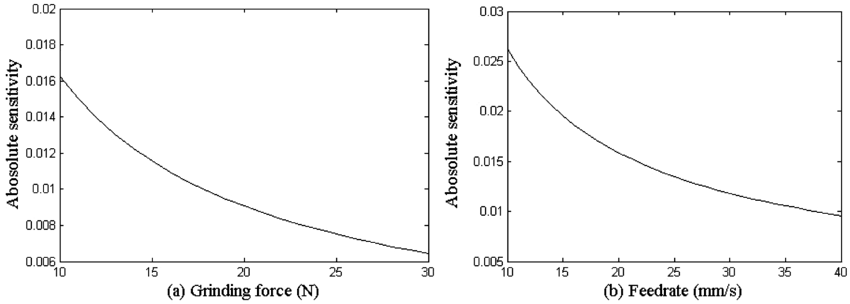
In the range of experimental parameters, = 20 mm/s, = 15 m/s, F = 20N, surface roughness, surface material removal depth of the grinding head feed rate, grinding force, grinding head line speed absolute sensitivity model. As in Eq. (3):

$$\begin{array}{l} S_{R_a}^{V_w} = 0.14 V_w^{-0.727}, S_{R_a}^{F} = 0.114 F^{-0.845}, S_{R_a}^{V_s} = -0.169 V_s^{-1.108} \\ S_{H}^{V_w} = -82.97 V_w^{-1.164}, S_{H}^{F} = 31.88 F^{-0.827}, S_{H}^{V_s} = 23.26 V_s^{-0.902} \end{array} \tag{3}$$

From the relative sensitivity analysis, it can be seen that the surface roughness is the most sensitive to the change of the feed rate of the grinding head when the TC11 titanium alloy is grinding, and the material removal depth is the most sensitive to the grinding force.

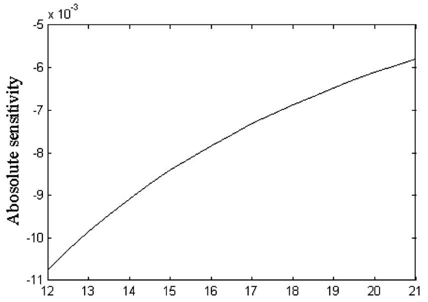
According to Eq. (3), the absolute sensitivity curve of the surface roughness to the grinding process parameters is obtained, as is shown in Fig. 6(a–c).

As can be seen from Fig. 6(a), the absolute sensitivity of the [18N, 30N] in the grinding force interval is less than the [10N, 18N] interval. That is, when the grinding force changes from 18N to 30N, the surface roughness curve is smooth. Similarly, the Fig. 6(b) shows that when the feed rate changes from 20 mm/s to 40 mm/s, the surface roughness curve is relatively smooth. Figure 6(c) shows that when the grinding tool speed transforms from 16 m/s to 21 m/s, the surface roughness curve is relatively also smooth.



(a) Grinding force (N)

(b) Feedrate (mm/s)



(c) Linespeed (m/s)

Fig. 6. The absolute sensitivity of surface roughness to grinding parameters

Similarly, the absolute sensitivity curve of the surface removal depth to the grinding parameters can be obtained. In the grinding force interval [18N, 30N] the absolute sensitivity value is less than [10N, 18N] interval, that means, when grinding force changes from 18N to 30N, the surface removal depth curve is relatively smooth.

The same, when the feed rate changes from 20 mm/s to 40 mm/s, the surface removal depth curve is relatively smooth. When the grinding line speed changes from 16 m/s to 21 m/s, the curve of the removal depth of the surface becomes relatively smooth.

3.4 Optimization of Grinding Process Parameters

Based on the single factor grinding process parameter experiment, the characteristic parameters of the grinding tool are firstly selected as follows: silicon carbide grinding head, particle size 400 #. In the optimization of the grinding parameters, it is necessary to consider not only whether the parameters are in the stable interval but also the requirements of the grinding surface characteristics and the sensitivity of the grinding parameters to the grinding surface characteristics. As shown in Table 1.

Table 1. Preferably grinding parameters of the process parameters interval

Category	Parameter range	Roughness range	Material removal
Feed rate (mm/s)	[20, 40]	<0.5	<40 μm
Grinding force (N)	[18, 30]	<0.5	<40 μm
Grinding line speed (m/s)	[16, 21]	<0.5	<40 μm

Based on the analysis above, this paper obtains the direction of the relatively stable grinding process parameters: grinding head feed speed Vw → 30 mm/s, grinding line speed Vs → 18 m/s, grinding force → 24N. Under these grinding conditions, with the use of 400 # silicon carbide grinding head, the TC11 alloy plate material was carried out to the grinding test. The surface roughness value was 0.26 μm and the single removal depth was 31 μm.

3.5 Research on Grinding Attitude Angle Based on Optimized Parameter Interval

It can be found that the quality of the surface of the workpiece would be significantly different when the grinding tool was tilted at a different grinding point from the surface of the workpiece. Different tilt angles can have a complex effect on the speed of the grinding head, the size of the contact area, the condition of the chip, and the wear. In order to study the relationship between the grinding attitude angle and the processing effect. The experiment parameters that affect the grinding quality of the robot are grinding force, grinding angle, grinding feed rate, grinding line speed, track spacing, etc. As shown in Fig. 7.

The surface roughness value of the sample after grinding was used as the response index, and the electric screw speed, the grinding force, the line spacing and the inclination angle were used as the four factors to carry out the 4-factor-3-level orthogonal test. During the grinding process, the surface was cooled with air, the depth of depression was 1 mm, and the feed rate was 1000 mm/min.

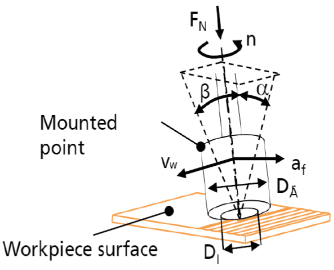


Fig. 7. Grinding process modeling

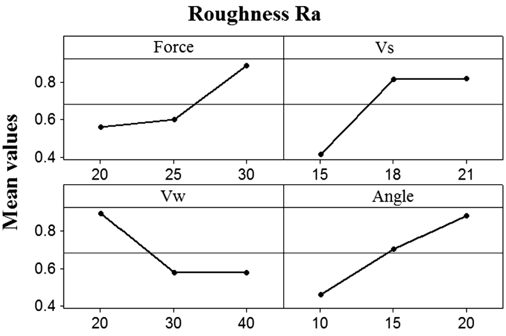


Fig. 8. Experimental results

As can be seen from Fig. 8, when the linear velocity is 21 m/s during the grinding process, the grinding force is 20 N, the feed rate is 30 mm/s, the inclination angle is 10°, the surface roughness can be minimized, with the uniform of the surface and no obvious texture.

4 Simulation and Experiment of Blade Grinding

4.1 Robot Grinding Platform

The turbine blade was selected as the experimental subject, whose material is titanium alloy TA 11. Its surface has a serious milling texture and the surface roughness value could reach above Ra0.9. According to processing requirements, the blade roughness after grinding must be less than 0.4. The hardware model and performance indicators of the construction process system are shown in the following Table 2.

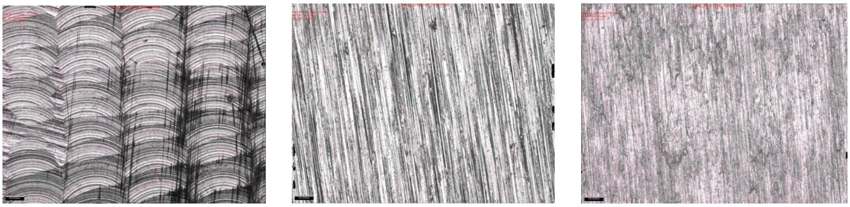
Table 2. List of experimental hardware

Hardware	Model	Performance indicators
Robot	Kuka KR210-2	6 degrees of freedom; repeat positioning accuracy 0.06 mm
Force controller	FerRobotics ACF 110-10	Force accuracy 1N; Reaction time 4 ms
Electric spindle	NSK E4000	Max. speed 40000 min^{-1}; Max. output 1,200 W
Grinding tool	Artifex EK120	Tool diameter ø:−5 mm, chamfer

Turbine blade surface is a complex surface and its processing is particularly difficult. In the process of blade grinding, in order to make the grinding wheel axis and the blade surface method to maintain a certain position, it is nessary to adjust the attitude of the robot constantly. This process must rely on CAM software and robot offline programming software. Firstly, the blade CAD model is obtained and the grinding area is selected. Then, the grinding trajectory is set according to the process parameters. Finally, the robotic program is used to generate the robot executable program.

4.2 Quality Inspection of Blade

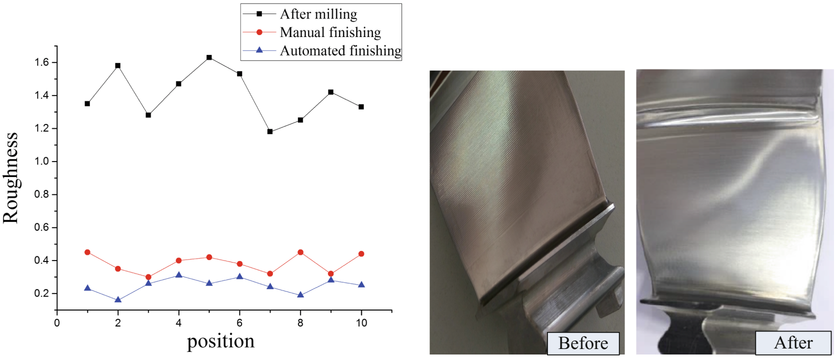
After grinding, the contour error of turbine blades was tested. At the time of testing, the specimen body was divided into several sections, and the precision of the blade shape in each section was about ±0.04 mm. In order to further verify the processing effect of the grinding process on the blade surface, the Infinite Focus G4 automatic zoom 3D surface measuring instrument was used to compare the microstructure before and after grinding. As shown in Fig. 9.



（a）After Milling （b）Manual Finishing （c）Automated Finishing

Fig. 9. Surface morphology under different grinding processes

Figure 10(a) shows more clearly of the different processing methods under the blade surface quality, after grinding the surface texture is basically eliminated. At the same time, in this paper a comparison with the robot grinding and artificial polishing after the surface roughness has completed.



(a) **(b)**

Fig. 10. (a) Roughness in three different grinding modes (b) The grinding quality of the blade after the preferred process parameters

After grinding, it can be seen from the Fig. 10(b) that the surface roughness of the blade has been significantly reduced. Robot grinding is better than manual grinding, and robots can have obvious advantages in efficiency.

5 Conclusions

1. This paper proposes a robot flexible grinding system which composed of robot and control cabinet, ACF flexible force controller, spindle, grinding tools and workbench. It is proven to be able to achieve automatic grinding and improve the grinding efficiency.
2. A grinding process is proposed based on the robot grinding platform, and a suitable grinding condition and process parameters are obtained. The texture left after the milling of the blade is substantially eliminated and the minimum roughness Ra can reach 0.16 μm. This method improves the surface uniformity and integrity of the blade grinding.
3. The turbine blade was subjected to grinding experiment with suitable process parameters. The results show that the flexible grinding system developed in this paper is suitable for the blade grinding process, which can provide an effective and quick way for the blade grinding.

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