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Sensitivity of surface roughness to flexible polishing parameters of abrasive cloth wheel and their optimal intervals †

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Abstract

High-speed rotating abrasive cloth wheel is a highly flexible material that can be used to polish aviation engine blades. In this study, sensitivity and relative sensitivity to processing parameters were described on the basis of an empirical model of surface roughness to control the polishing of rough surfaces with abrasive cloth wheels. A mathematical model of the sensitivity and relative sensitivity of surface roughness to processing parameters was also established on the basis of an orthogonal test of polishing TC4 blade workpieces by utilizing abrasive cloth wheels. The sensitivity of the analytical method for processing parameter interval was examined, and the division principle and approach for the stable and unstable ranges of processing parameters were proposed. The influence curve of polishing parameters on surface roughness was obtained by combining the analyzed ranges in the orthogonal test. The optimization of processing parameter interval was also presented to identify the optimal intervals of surface-roughness-oriented polishing parameters of abrasive cloth wheels. The polishing test based on an aviation engine blade confirmed that the optimal intervals of the parameters were reliable. This research provides a basis for theoretical studies and tests to evaluate blade polishing technique with abrasive cloth wheels and surface roughness control.

Keywords: Abrasive cloth wheel; Polishing; Aviation engine blade; Surface roughness; Sensitivity; Optimal intervals

1. Introduction

Surface roughness influences the functional characteristics, fatigue durability, and surface friction properties of a workpiece [1]. Aviation engine blades with unqualified surface roughness easily suffer from fatigue failure, deformation, or breakage in high-temperature and high-pressure service environments [2], and these negative factors likely cause severe consequences. Machine shaping blades are spatial free-form surfaces with evident milling remain height [3]. Therefore, a polishing method is necessary to remove remains to achieve satisfactory surface roughness [4] and thus improve blade surface quality and aircraft engine performance. Spatial complex surface polishing has been extensively investigated, and excellent results have been obtained.

Robotic [5-7] and Computer numerical control (CNC) machines [8-10] are widely accepted as polishing machines in foreign countries. These machines combined with route planning [8] and visual positioning technologies [6] have yielded ideal complex surface polishing effects. However, CNC machines are costly [11] and unable to control polishing force [8]. By comparison, robots present large polishing track errors [6]. Pan et al. [11], Zeng and Blunt [12] and Ji and Zhang et al. [13-15] from Zhejiang University of Technology used a gasbag as a polishing tool for spherical lens, medical cobalt-chromium alloy, and mold surface, respectively. They achieved an ideal polishing effect by reasonably controlling processing parameters. Several non-contact polishing techniques, such as magnetofluid [16, 17], abrasive fluid [18], and electrofluid [19, 20], have also been proposed for complex geometries. However, these techniques provide low material removal rates, low polishing efficiency [16], and high costs [21]. Abrasive belts [22-24] have also been used as a polishing tool because of high polishing efficiency, but these materials are inapplicable for blisks in narrow vent passages because of a large grinding head [25].

With low volume, simple structure, and good flexibility, abrasive cloth wheels can be used to polish blisks in narrow vent passages. For instance, an abrasive cloth wheel on an independently developed five-axis CNC machine is used to polish a blade and thus reduce interference and improve adaptivity and polishing efficiency of the "shape-followed contact" between a grinding tool and a polishing surface [26]. The radius of abrasive cloth wheels increases during high-speed rotation because of centrifugal force. As a result, surfaces

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exhibit good elasticity and "shape-followed contact" during polishing. Abrasive cloth wheels can prevent "under-polishing" or "over-polishing" and maintain a stable polishing force. Thus, these materials enhance the polishing efficiency.

The polishing parameters of abrasive cloth wheels indicate surface roughness. However, polishing parameters should be determined on the basis of different remains in practical polishing, especially polishing aviation engine blades with complex surfaces, which cause nonlinear remains. For example, processing parameters, such as rotation speed, compression depth, and abrasive size of the abrasive cloth wheels, should be adjusted to different extents on the basis of the actual surface roughness when aviation engine blades are polished with an abrasive cloth wheel. However, adjustment ranges of polishing parameters of abrasive cloth wheels have yet to be established for reference. Therefore, this study proposed a method to analyze the sensitivity of surface roughness to the processing parameters of abrasive cloth wheels and obtained the optimal intervals of processing parameters.

In this paper, Sec. 2 introduces the method for the sensitivity analysis of surface roughness to the processing parameters of an abrasive cloth wheel. Sec. 3 presents an orthogonal test based on the analysis of the polishing parameters of the abrasive cloth wheel and describes a mathematical model of the sensitivity and relative sensitivity of surface roughness to processing parameters. Sec. 3 further analyzes the sensitivity of surface roughness in different intervals of processing parameters and determines the stable and unstable ranges of processing parameters. Sec. 4 examines the effects of different processing parameters on surface roughness by range analysis and proposes a method that determines the optimal intervals of processing parameters. Sec. 4 also identifies the optimal intervals of polishing parameters of the abrasive cloth wheel. Sec. 5 evaluates the reliability of the optimal intervals of polishing parameters by performing a polishing test on an aviation engine blade.

2. Sensitivity analysis of surface roughness to processing parameters

2.1 Sensitivity of surface roughness to processing parameters

Sensitivity refers to the degree of sensitivity or variation rate of the optimal design goal to variations in design variables. This value is determined to recognize significant and insignificant design variables in the optimal design of objective function. Thus, variable parameters can be effectively and accurately controlled and optimized, and the optimization program can be modified to help achieve the optimal objective.

Sensitivity shows the variations in the objective function $f(x)$ with its variables $x=(x_1,x_2,...,x_j,...,x_n)$. If $f(x)$ is derivable, the first-order sensitivity S in the continuous system can be expressed as follows [27]:

$$S(x_i)=\frac{\partial f(x)}{\partial x_i}. \tag{1}$$

The orthogonal test-based empirical model of surface roughness polished by an abrasive cloth wheel can be expressed as follows:

$$R_a = f(\omega, p, a_p, v_f, P) = c_0\omega^{c_1} p^{c_2} a_p{}^{c_3} v_f{}^{c_4} P^{c_5} \tag{2}$$

where R_a is the roughness; ω, p, a_p, v_f and P are the rotation speed, line spacing, compression depth, feed rate, and abrasive size of the abrasive cloth wheel, respectively; c_0 is a constant; and c_1, c_2, c_3, c_4 and c_5 are indexes. The analysis method for the sensitivity of surface roughness to processing parameters was evaluated on the basis of this universal empirical model.

The sensitivity and relative sensitivity of surface roughness to processing parameters were proposed. The sensitivity of surface roughness to processing parameters refers to the sensitivity degree or variation rate of surface roughness to variations in single processing parameters:

$$\left.\begin{aligned}
S^{\omega}{}_{R_a} &= \frac{\partial f(\omega,\overline{p},\overline{a_p},\overline{v_f},\overline{P})}{\partial \omega}\\
S^{p}{}_{R_a} &= \frac{\partial f(\overline{\omega},p,\overline{a_p},\overline{v_f},\overline{P})}{\partial p}\\
S^{a_p}{}_{R_a} &= \frac{\partial f(\overline{\omega},\overline{p},a_p,\overline{v_f},\overline{P})}{\partial a_p}\\
S^{v_f}{}_{R_a} &= \frac{\partial f(\overline{\omega},\overline{p},\overline{a_p},v_f,\overline{P})}{\partial v_f}\\
S^{P}{}_{R_a} &= \frac{\partial f(\overline{\omega},\overline{p},\overline{a_p},\overline{v_f},P)}{\partial P}
\end{aligned}\right\} \tag{3}$$

where $\overline{\omega}$, $\overline{p}$, $\overline{a_p}$, $\overline{v_f}$ and $\overline{P}$ are the means of the parameters in the test.

The sensitivity of surface roughness to processing parameters indicates the variation rate of surface roughness within a certain parameter range. Therefore, ranges of processing parameters under one surface roughness level could be obtained ideally according to this sensitivity.

2.2 Relative sensitivity of surface roughness to processing parameters

Although the sensitivity of surface roughness to processing parameters can reflect the variation rate of surface roughness within a certain parameter range well, this parameter cannot comprehensively indicate the sensitivity degree of surface roughness to processing parameters. Determining which processing parameters are sensitive (such as rotation speed, line spacing, and abrasive size of the abrasive cloth wheel) and insensitive to surface roughness is crucial in the selection of processing parameters. Insensitive parameters could determine a wide range, whereas sensitive parameters must be selected carefully. Hence, the concept of relative sensitivity of surface roughness to processing parameters was proposed. Relative sensitivity reflects the sensitivity degree of surface roughness to processing parameters comprehensively.

Eq. (3) shows that surface roughness presents different dimensions of sensitivity to different processing parameters and can only reflect the effects of different processing parameters on surface roughness. For a comprehensive comparison of the effects of processing parameters on surface roughness, the sensitivity dimensions of processing parameters in Eq. (3) should be unified.

Hence, if $f(x)$ is derivable and is not equal to 0, the relative sensitivity is expressed as follows [27]:

$$S^{'}(x) = S(x)\frac{x_i}{f(x)} = \frac{\partial f(x)}{\partial x_i}\frac{x_i}{f(x)} . \tag{4}$$

For the surface roughness model expressed in Eq. (2), the relative sensitivity is described as follows:

$$\left.\begin{aligned}
S'^{\omega}_{R_a} &= S^{\omega}_{R_a}\frac{\omega}{f(\bar\omega,\bar p,\bar a_p,\bar v_f,\bar P)}\\
S'^{p}_{R_a} &= S^{p}_{R_a}\frac{p}{f(\bar\omega,\bar p,\bar a_p,\bar v_f,\bar P)}\\
S'^{a_p}_{R_a} &= S^{a_p}_{R_a}\frac{a_p}{f(\bar\omega,\bar p,\bar a_p,\bar v_f,\bar P)}\\
S'^{v_f}_{R_a} &= S^{v_f}_{R_a}\frac{v_f}{f(\bar\omega,\bar p,\bar a_p,\bar v_f,\bar P)}\\
S'^{P}_{R_a} &= S^{P}_{R_a}\frac{P}{f(\bar\omega,\bar p,\bar a_p,\bar v_f,\bar P)}
\end{aligned}\right\} . \tag{5}$$

The relative sensitivity of surface roughness to processing parameters reflects the sensitivity degree (or variation) of surface roughness to processing parameters comprehensively and provides the calculation reference and method to determine processing parameters. The sensitivity of surface roughness to processing parameters also indicates the sensitivity degree or variation of surface roughness to variations in single parameter and provides a calculation reference and method for the selection, adjustment, and variation of single processing parameters.

3. Polishing test

3.1 Test platform

The independently developed five-axis CNC machine was used as the polishing machine (Fig. 1). The machine possesses three rectilinear coordinate axes and three rotational coordinate axes. These axes of motion include rectilinear axes (*X*, *Y* and *Z*), rotational axis of blade (*U*), swing axis of blade (*C*), and swing axis of flexible grinding head (*A*). The principal axis *A* causes the real-time adjustment of the grinding head to pass through three microdisplacement cylinders in radial uniform distribution and one axial micro-displacement cylinder

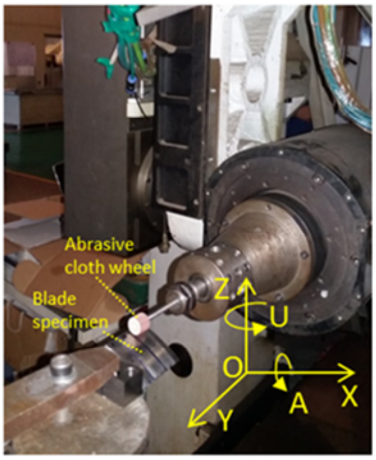


Fig. 1. Five-axis CNC polishing machine.

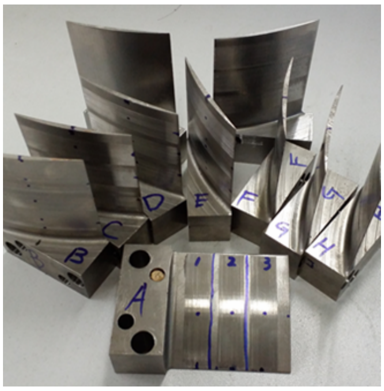


Fig. 2. TC4 blade samples.

according to blade geometric profile changes in the CNC program. This configuration protects the effective contact between the abrasive cloth wheel and blade geometric profile. Thus, flexible adaptive polishing is achieved. The working principle is introduced in another study [1].

In the test, 10 TC4 blade samples (A-J) were used (Fig. 2). The back and basin of each blade were divided into three zones from the root to the tip and numbered 1, 2 and 3, respectively. For example, three zones on the back of blade A were marked as A1, A2 and A3.

TC4 is characteristic of easy adhesion, high grinding temperature, strong chemical activity, and low grinding ratio in the grinding process. Considering the demands for adequate flexibility of the abrasive cloth wheel in polishing, this paper selected a 8.5 mm × 14 mm × *P* (initial radius r_0 × thickness *L* × abrasive size *P*) (P = 60#, 330# and 600#) green SiC cloth-based abrasive cloth wheel as the grinding tool.

In the polishing test, each randomly selected polishing zone was polished thrice with a group of processing parameters. Five measuring points were selected from the polishing zones randomly before and after polishing. Surface roughness was measured by a Mar Surf XR 20 surface roughometer (sampling length = 0.8 mm and evaluation length = 4 mm) through

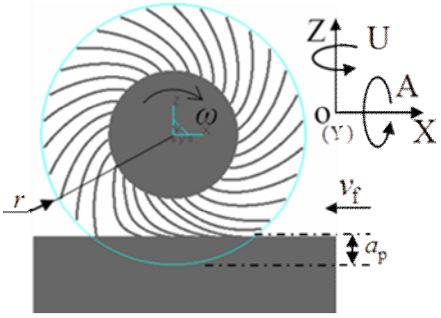


Fig. 3. Polishing principle of abrasive cloth wheel.

a vertical polishing track approach. The mean value was obtained as the final result.

3.2 Analysis of processing parameters

Fig. 3 shows that the radius of the abrasive cloth wheel increases during rotation at the speed of ω (r/min) under the influence of centrifugal force. It experiences radial compression from the polishing surface. Rotation speed (ω) and compression depth (a_p/mm) are the main influencing parameters of polishing force [2] and the key processing parameters that influence surface roughness [3]. The line spacing between polishing routes (p/mm) determines the number of polishing, whereas feed speed (v_f/mm/min) and abrasive size (P) influence the number of abrasive particles involved in polishing [3]. Therefore, the processing parameters of the abrasive cloth wheel include ω, a_p, v_f, P and p.

Isoparametric line method [25] employed for track planning and cutter radius in CNC programming was r-a_p, which ensured that the abrasive cloth wheel possesses stable compression depth during polishing. Given that the horizontal line spacing method can eliminate external waviness of the blade effectively [26], horizontal line spacing-based polishing, that is, polishing along the milling track was employed in this paper.

4. Sensitivity analysis of surface roughness to processing parameter intervals

4.1 Relative sensitivity of surface roughness to processing parameters

The empirical model of polished surface roughness of abrasive cloth wheel was established based on the linear regression analysis of testing processing parameters and surface roughness in Table 1:

$$R_a = f(\omega, p, a_p, v_f, P) = \omega^{-0.065} p^{0.175} a_p^{-0.192} v_f^{0.163} P^{-0.244} \ . \tag{6}$$

The confidence coefficient was set as $\alpha = 0.05$. The significance of the model was tested by F-test and multiple correlation coefficient test method. $F = 65.64 > F_{0.01}(5, 18\text{-}5\text{-}1) = 5.06$. The multiple correlation coefficient was $R = 0.981$, and its minimum value was $R_{min} = 0.722$. Therefore, $R > R_{min}$. Both

Table 1. Experiments and results from central composite design.

ω (r/min)	p (mm)	a_p (mm)	v_f (mm/min)	P	R_a (μm)
4500	0.7	0.6	320	60	0.697
4500	1.2	0.9	220	600	0.349
4500	1.7	1.2	120	330	0.315
6000	0.7	0.6	220	600	0.332
6000	1.2	0.9	120	330	0.196
6000	1.7	1.2	320	60	0.604
7500	0.7	0.9	320	330	0.230
7500	1.2	1.2	220	60	0.493
7500	1.7	0.6	120	600	0.417
4500	0.7	1.2	120	600	0.271
4500	1.2	0.6	320	330	0.332
4500	1.7	0.9	220	60	0.570
6000	0.7	0.9	120	60	0.485
6000	1.2	1.2	320	600	0.357
6000	1.7	0.6	220	330	0.323
7500	0.7	1.2	220	330	0.281
7500	1.2	0.6	120	60	0.519
7500	1.7	0.9	320	600	0.383

F-test and multiple correlation coefficient test confirmed that the established empirical model of surface roughness fits well with test data.

We substituted Eq. (6) into Eq. (5) and calculated that the relative sensitivity of surface roughness to processing parameters is the exponent of parameters: $S'^{\,\omega}_{R_a} = -0.065$, $S'^{\,p}_{R_a} = 0.175$, $S'^{\,a_p}_{R_a} = -0.192$, $S'^{\,v_f}_{R_a} = 0.163$ and $S'^{\,P}_{R_a} = -0.244$.

Therefore, the polishing surface roughness of abrasive cloth wheel is mostly sensitive to abrasive size, followed by compression depth, line spacing, feed rate, and rotation speed. Surface roughness is basically sensitive to line spacing and feed rate.

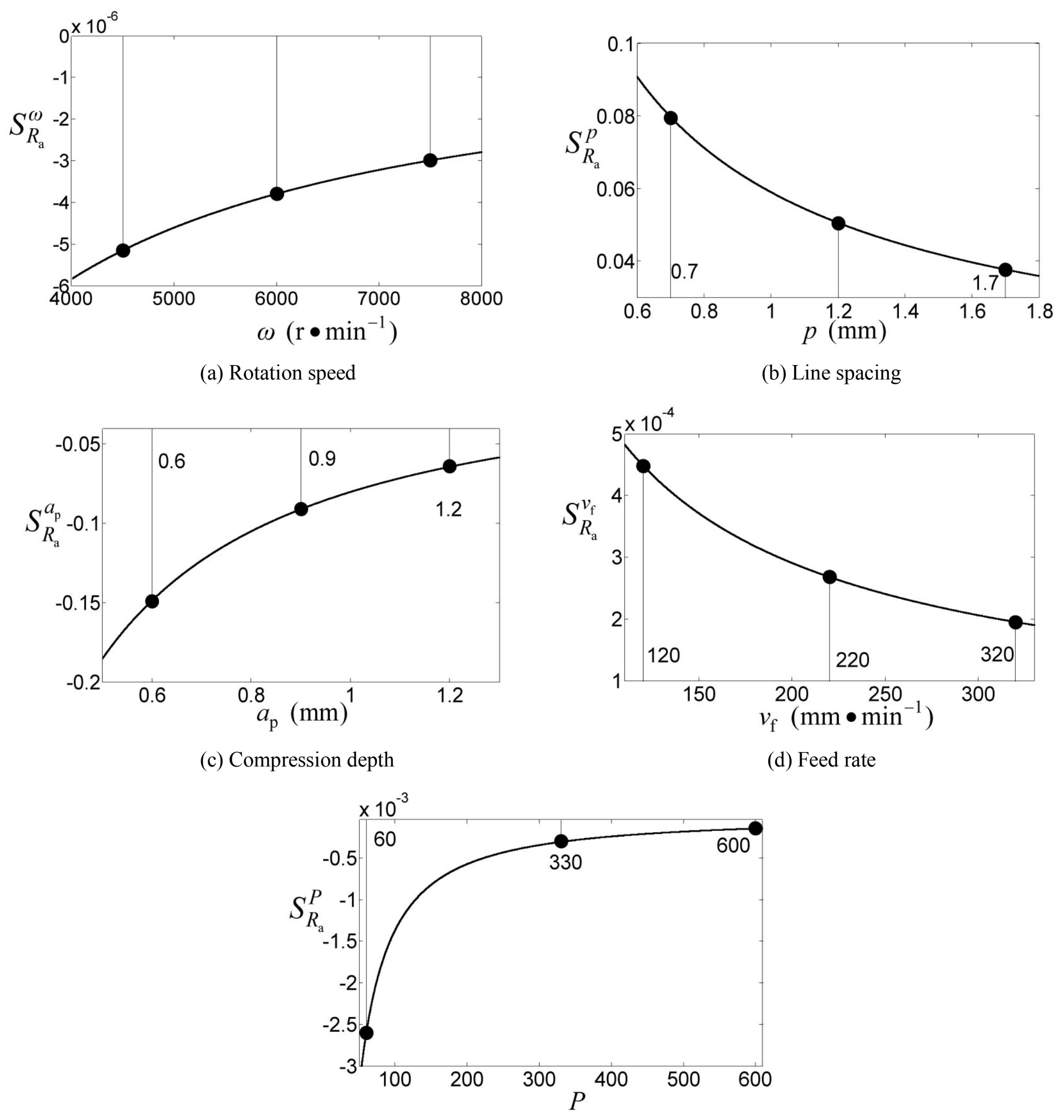
4.2 Sensitivity of surface roughness to processing parameters

4.2.1 Calculation of sensitivity model

According to Eq. (3), the sensitivity model of surface roughness to polishing parameters of abrasive cloth wheel is:

$$\left.\begin{aligned}
S^{\omega}_{R_a} &= -0.065 \times \omega^{-1.065}\, \overline{p}^{\,0.175}\, \overline{a_p}^{\,-0.192}\, \overline{v_f}^{\,0.163}\, \overline{P}^{\,-0.244} \\
S^{p}_{R_a} &= 0.175 \times \overline{\omega}^{\,-0.065}\, p^{-0.825}\, \overline{a_p}^{\,-0.192}\, \overline{v_f}^{\,0.163}\, \overline{P}^{\,-0.244} \\
S^{a_p}_{R_a} &= -0.192 \times \overline{\omega}^{\,-0.065}\, \overline{p}^{\,0.175}\, a_p^{-1.192}\, \overline{v_f}^{\,0.163}\, \overline{P}^{\,-0.244} \\
S^{v_f}_{R_a} &= 0.163 \times \overline{\omega}^{\,-0.065}\, \overline{p}^{\,0.175}\, \overline{a_p}^{\,-0.192}\, v_f^{-0.837}\, \overline{P}^{\,-0.244} \\
S^{P}_{R_a} &= -0.244 \times \overline{\omega}^{\,-0.065}\, \overline{p}^{\,0.175}\, \overline{a_p}^{\,-0.192}\, \overline{v_f}^{\,0.163}\, P^{-1.244}
\end{aligned}\right\} . \tag{7}$$

In the ranges of test parameters, $\overline{\omega} = 6000$ r/min, $\overline{p} = 1.2$ mm, $\overline{a_p} = 0.9$ mm, $\overline{v_f} = 220$ mm/min and $\overline{P} = 330^{\#}$.



(a) Rotation speed (b) Line spacing

(c) Compression depth (d) Feed rate

(e) Abrasive size

Fig. 4. Sensitivity curves of surface roughness for processing parameters.

The corresponding sensitivities are:

$$\left.\begin{array}{l} S_{R_a}^{\omega} = -0.04 \times \omega^{-1.065} \\ S_{R_a}^{p} = 0.059 \times p^{-0.825} \\ S_{R_a}^{a_p} = -0.08 \times a_p^{-1.192} \\ S_{R_a}^{v_f} = 0.024 \times v_f^{-0.837} \\ S_{R_a}^{P} = -0.422 \times P^{-1.244} \end{array}\right\}. \tag{8}$$

4.2.2 Analysis of sensitivity curve

The sensitivity curves of surface roughness to rotation speed, line spacing, compression depth, feed rate, and abrasive size obtained from Eq. (8) are shown in Fig. 4. According to the analysis of relative sensitivity, surface roughness is mostly sensitive to abrasive size, followed by compression depth, line spacing, feed rate, and rotation speed successively. Therefore, rotation speed could be neglected in further selection of test parameter ranges. In other words, rotation speed could be selected randomly within the preset range, but abrasive size, compression depth, line spacing, and feed rate have to be further optimized.

In Fig. 4(a), the sensitivity of surface roughness to rotation speed in the interval of [4500 r/min, 6000 r/min] is higher than that in the interval of [6000 r/min, 7500 r/min]. In Fig. 4(b), the sensitivity of surface roughness to line spacing in the interval of [0.7 mm, 1.2 mm] is higher than that in the interval of [1.2 mm, 1.7 mm]. This finding indicated that surface roughness changes slightly when line spacing increases from 1.2 mm to 1.7 mm. Similarly, surface roughness changes mildly when compression depth increases from 0.9 mm to 1.2 mm [Fig. 4(c)] when feed rate increases from 220 mm/min to 320 mm/min [Fig. 4(d)] and when the abrasive size expands from $330^{\#}$ to $600^{\#}$ [Fig. 4(e)].

Table 2. Stable range and unstable range of polishing parameters.

Parameters	Stable range	Unstable range
ω (r · min^{-1})	[6000, 7500]	[4500, 6000]
p (mm)	[1.2, 1.7]	[0.7, 1.2]
a_p (mm)	[0.9, 1.2]	[0.6, 0.9]
v_f(mm · min^{-1})	[220, 320]	[120, 220]
P	[330$^{\#}$, 600$^{\#}$]	[60$^{\#}$, 330$^{\#}$]

4.3 Stable and unstable ranges of processing parameters

The stable range of processing parameters refers to the parameter range in which the surface roughness is insensitive. The unstable range of processing parameters refers to the parameter range in which the surface roughness is sensitive. For an orthogonal test involving n factors (N_1, N_2,..., N_n) and m levels (M_1, M_2, ..., M_m), a method to divide stable range and unstable range of processing parameters is proposed: (1) According to sensitivity curves, changes in sensitivity to factors N_i (i = 1, 2, …, n) in $m-1$ intervals such as [M_1, M_2] and [M_2, M_3] are calculated and expressed as A_1, A_2, …, A_{m-1}; (2) calculate the mean of A_1, A_2, …, A_{m-1}, which is expressed as A_0. The range of A_j (j = 1, 2, …, m−1) >A_0 is defined as the unstable range, and the range of $A_j < A_0$ is defined as the stable range. The stable and unstable ranges of rotation speed, line spacing, compression depth, feed rate, and abrasive size in this experiment are determined according to the corresponding sensitivity curves (Table 2).

5. Optimal intervals of polishing parameters of the abrasive cloth wheel

5.1 Selection of polishing parameter intervals based on surface roughness

A selection method for processing parameter intervals according to surface roughness was proposed on the basis of sensitivity analysis of surface roughness to processing parameters and the intuitive range analysis of the original orthogonal test data.

(1) According to the analysis of the relative sensitivity of surface roughness to processing parameters, the processing parameters were screened, and the sensitive and insensitive parameters were determined.

(2) The stable and unstable ranges of sensitive processing parameters were determined according to the analysis of the sensitivity of surface roughness to processing parameters. The values of insensitive processing parameters could be determined within the testing ranges. If insensitive parameters are easily controlled, their optimal interval could be determined using the following steps.

(3) Surface roughness in stable and unstable ranges of processing parameters were calculated and compared on the basis of the range analysis of the original orthogonal test data.

(4) If surface roughness in the stable ranges (calculated in step (3)) was superior to that in the unstable ranges, the stable ranges are selected as the optimal intervals.

(5) If surface roughness in stable ranges (calculated in step (3)) is inferior to that in unstable ranges, the unstable ranges are selected as as the optimal intervals.

(6) Given that the optimal intervals determined in step (5) are unstable ranges, a continuous planning test is necessary to adjust the parameters and determine smaller stable and unstable ranges.

5.2 Parameter interval optimization based on surface roughness

The relative sensitivity of surface roughness to processing parameters in the polishing test was analyzed firs by the above method, which concluded that surface roughness was mostly sensitive to abrasive size, followed by compression depth, line spacing, feed rate, and rotation speed. Second, the stable and unstable ranges of abrasive size, compression depth, line spacing, and feed rate were determined (Table 2). Third, the variation range of surface roughness in the stable ranges and unstable ranges of processing parameters (abrasive size, compression depth, line spacing, and feed rate) were obtained through the range analysis of the orthogonal test data (Fig. 5). Although changes in rotation speed influences surface roughness are the smallest, the changes are easily controllable and can be determined within the narrow range of surface roughness. In Fig. 5(a), surface roughness varies between 0.38 and 0.39 μm in the stable range of rotation speed and changes between 0.38 and 0.42 μm in its unstable range. In Fig. 5(b), surface roughness ranges between 0.37 and 0.38 μm in the unstable range of line spacing and between 0.37 and 0.43 μm in its stable range. In Fig. 5(c), surface roughness is lower than 0.37-0.39 μm in the stable range of compression depth and between 0.37 and 0.44 μm in its unstable range. In Fig. 5(d), surface roughness is between 0.39 and 0.43 μm in the stable range of feed rate and between 0.37 and 0.39 μm in its unstable range. In Fig. 5(e), surface roughness is between 0.28 and 0.35 μm in the stable range of abrasive size and lower than 0.28-0.56 μm in its unstable range.

The TC4 parameter interval of the abrasive cloth wheel (Table 3) could ensure good surface roughness. The optimal intervals of line spacing and feed rate are within the unstable range [0.7 mm, 1.2 mm] and [120 mm/min, 220 mm/min], respectively. The adjustment of line spacing and feed rate require further calculation of the stable and unstable ranges. Although surface roughness is insensitive to rotation speed, rotation speed can be determined in the range of small surface roughness because of its easily controllable characteristic.

5.3 Polishing test

Two TC4 blades (A and B) from a blade disc of aviation engine were polished under parameters in the non-optimal intervals (5000 r/min, p = 1.5 mm, a_p = 0.8 mm, v_f = 300 mm/min and P = 200$^{\#}$) and optimal intervals (6500 r/min, p = 1 mm, a_p = 1 mm, v_f = 150 mm/min and P = 400$^{\#}$) (Fig. 6).

Each blade was polished thrice. The abrasive cloth wheel was 8.5 mm × 14 mm. Five points on the blade surface were selected randomly to measure surface roughness perpendicular to the polishing track by using Mar Surf M300C roughometer before and after the polishing. The means were used as the final measurement result.

Table 3. Parameter interval optimization.

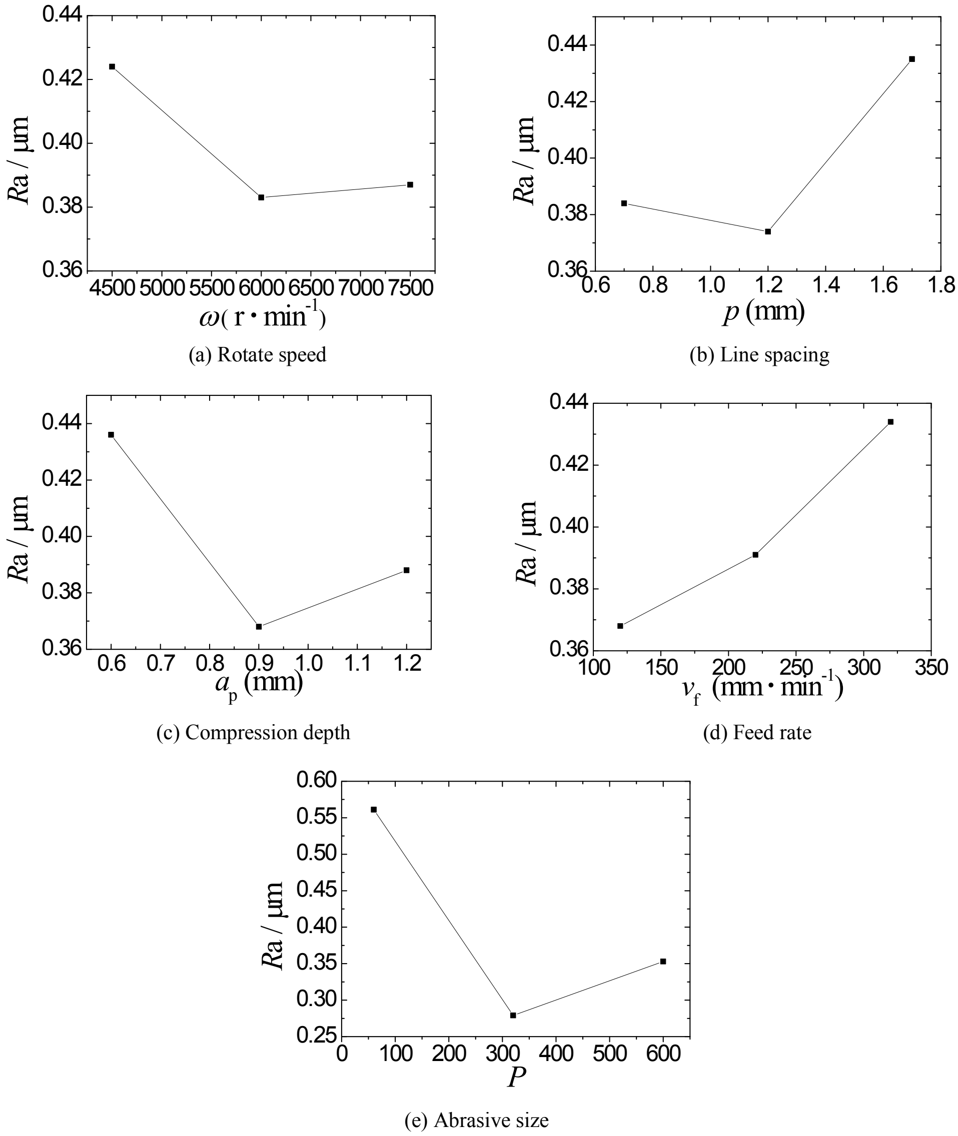
Parameters	Interval optimization	Range	Roughness (μm)
ω (r · min^{-1})	[6000, 7500]	Stable	< 0.39
p (mm)	[0.7, 1.2]	Unstable	< 0.38
a_p (mm)	[0.9, 1.2]	Stable	< 0.39
v_f (mm · min^{-1})	[120, 220]	Unstable	< 0.39
P	[330$^{\#}$, 600$^{\#}$]	Stable	< 0.35

Before the surface was polished, the mean surface roughness of *A* and *B* were 1.12 and 1.26 μm, respectively. *A*, which was polished under the parameters in the non-optimal intervals, presented a mean surface roughness of 0.41 μm, whereas *B*, which was polished under the parameters in the optimal intervals, showed a mean surface roughness of 0.32 μm.

The test results confirmed that the optimal intervals of the polishing parameters of the abrasive cloth wheel are reliable and thus contribute a significantly more efficient polishing effect than non-optimal intervals do, as indicated by decreased surface roughness and eliminated surface texture of the blade (Fig. 7).

6. Conclusions

(1) The calculation concepts and methods for the sensitivity



(a) Rotate speed (b) Line spacing

(c) Compression depth (d) Feed rate

(e) Abrasive size

Fig. 5. Influencing curves of polishing parameters on surface roughness.

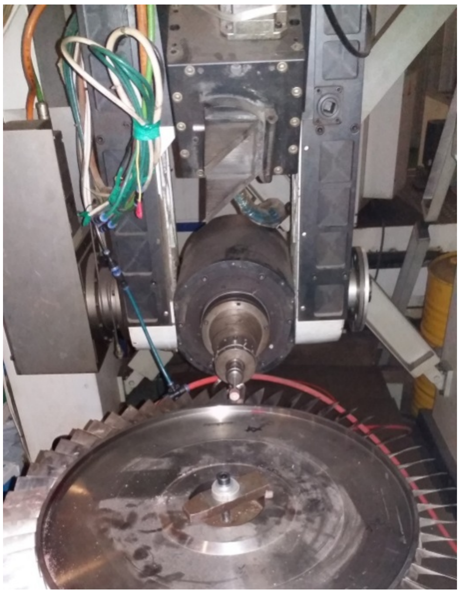
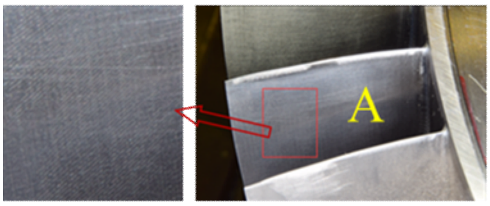
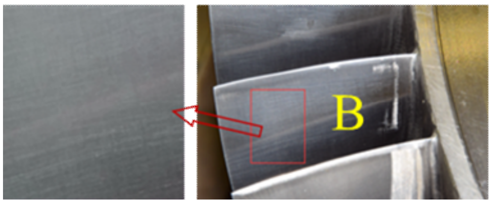


Fig. 6. Polishing test.



(a) Unstable parameters ($R_a = 0.41\ \mu$m)



(b) Stable parameters ($R_a = 0.32\ \mu$m)

Fig. 7. Polishing effect.

and relative sensitivity of polishing surface roughness are proposed. The concepts of stable range and unstable range of polishing parameters are also presented.

(2) The stable and unstable ranges of polishing parameters are determined on the basis of the orthogonal test results. The polishing surface roughness of the abrasive cloth wheel is mostly sensitive to abrasive size, successively followed by compression depth, line spacing, feed rate, and rotation speed.

(3) The determination method for the optimal intervals of polishing parameters is proposed by considering surface roughness. The optimal intervals of rotation speed, line spacing, compression depth, feed rate, and abrasive size are 6000-7500 r/min, 0.7-1.2 mm, 0.9-1.2 mm, 120-220 mm/min and $330^{\#}$-$600^{\#}$, respectively. The variation range of surface roughness in the optimal intervals of processing parameters is also determined.

(4) The polishing test on an aviation engine blade confirms that the optimal intervals of polishing parameters are reasonable and reliable.

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Nomenclature

a_p : Compression depth
ω : Rotate speed
v_f : Feed rate
p : Line spacing
P : Abrasive size
S_{R_a} : Sensitivity of surface roughness for processing parameters
S'_{R_a} : Relative sensitivity of surface roughness for processing parameters

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