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Investigation of the effect of vibration characteristics on the grinding performance of aero-engine blade tip

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Abstract

The machining quality of the blade tip has a great influence on the service performance and life of the aero-engine blade. The recent paper investigates the effect of vibration during the grinding process of the GH4169 nickel-based superalloy blade tip. Moreover, this paper proposes a theoretical model to link the unbalance of the grinding wheel, the vibration, and the surface topography characteristics of the blade. The results show that the blade vibration during grinding and the resulting non-linear change of the grinding depth could reduce the surface quality of the blade tip, and lead to differences in the surface quality of the blade tip in different areas, where the surface roughness in the entry area zone I is the largest, in the exit area zone III is the second largest, and the intermediate area zone II is the smallest. Grinding depth has a greater impact on the difference of the surface quality in the blade tip grinding process, especially when the grinding depth is greater than 4 μm , the difference of surface roughness increases significantly. On the other hand, the feed rate has little effect on the difference in surface quality. Adding damping block can reduce the surface roughness of the blade tip, however, it does not reduce the difference in surface quality.

Keywords: Blade tip; Nickel-based superalloy; Grinding process; Surface quality; Vibration characteristics

1. Introduction

The material properties, structure design, manufacturing process of aero-engine blades are crucial to the performance of the engine. With excellent oxidation resistance, corrosion resistance, structure stability, and other characteristics, nickel-based superalloys are widely used in aircraft engines, accounting for 40%-60% of the total engine materials[1–4]. Therefore, most of the engine blades are made of nickel-based superalloy. However, the excellent physical and mechanical properties make it a typical difficult-to-machine material[5,6].

At present, the manufacturing of aero-engine blades mainly adopts mechanical

processing methods, among which grinding plays an important role[7–10]. To improve the machining surface quality of nickel-based superalloy blades, researchers have carried out a large number of grinding experiments. Poletaev et al.[11] studied the effect of multi-coordinate creep-feed grinding on the surface quality of nickel-based superalloy blade, and revealed the influence of grinding conditions on the surface roughness and residual stress of the blade. Osterle et al.[12] carried out a study on IN738 nickel-based alloy blade grinding induced residual stress, and the results show that the grinding depth has the greatest influence on the surface residual stress, and continuous dressing can improve the surface topography of the grinding wheel and reduce the residual stress. Qing et al.[13] compared the grinding force, grinding ratio, grinding wheel wear, and surface integrity of four different kinds of nickel-based alloy blades in the grinding process. They found that the blade grinding with the alumina wheel is prone to surface defects and internal cracks. Huang et al.[14] proposed an adaptive trajectory planning approach of abrasive belt grinding for the aero-engine blade. By analyzing the relationship between the width of the contact wheel and curvature of the surface, the interference between them was avoided, and the accuracy and efficiency of blade grinding were greatly improved.

However, current research mainly focuses on the machining surface quality and accuracy of the blade surface, and there are few studies on the grinding quality of blade tip. In fact, poor machining quality of blade tip is easy to cause early cracks and even collapse of blades in the service process, which seriously affects the service life of aero-engines. Therefore, Eric et al.[15] used the elastic material in the blade fixture to position the blade in the radial direction in the process of blade tip grinding, and developed a special fixture to improve the machining stability of the blade tip to avoid any deflection in the aero-engine blade as it is a thin-walled part. In the grinding process, the feed direction of the grinding wheel is approximately perpendicular to the blade surface, which is easy to cause the vibration of the blade. This will inevitably affect the surface quality and service performance of the blade tip. To restrain the machining vibration of thin-walled parts such as blades, Moradi et al.[16] developed a tuneable vibration absorber, and proposed an optimization algorithm to determine the optimal value of absorber parameters. Xian et al.[17] found that polishing vibration is not stable in the process of polishing the aero-engine blade with the abrasive cloth wheel. They used the simulation models to obtain the frequency characteristics of the polishing force and rod vibration. Moreover, they calculated the best spindle speed range to avoid resonance during the polishing process, which provides a basis for reducing polishing vibration and improving blade polishing accuracy and efficiency. Hou et al.[18] proposed an approach to enhance the machining stability of titanium hollow blades by introducing multiple damping and rigid supporters to the blade machining system in the multi-axis milling process, which effectively suppressed up to 40% noise signal and improved the processing stability. Although there are many pieces of research about the machining stability of thin-walled parts, the research on the vibration characteristics of the blade tip is still insufficient. Therefore, it is necessary to conduct analysis and research on the vibration characteristics of nickel-based superalloy blade tip grinding and its influence on machining quality.

In this paper, the variation of blade tip vibration, grinding force, and surface quality under different grinding parameters of the blade tip of the aero-engine GH4169 nickel-based superalloy stator blade are studied. The influence of process parameters on blade vibration and the change of surface roughness of blade tip is mainly analyzed, and the theoretical relationship model between blade tip vibration characteristics and surface roughness is established. The reasons stands behind the difference in the surface quality of the blade tip were discovered and discussed. Furthermore, the variation of the surface roughness difference of the blade tip under different grinding parameters was revealed. The research results give important reference significance for improving the processing quality and service performance of aero-engine blades.

2 The proposed model

2.1 Grinding dynamic analysis

The main chemical composition and properties of the blade are shown in Table 1 and Table 2. It can be noticed that GH4169 nickel-based superalloys material contains a large amount of high melting point elements such as Cr, Ni, Mo, Nb, Ti, and constitutes austenitic with dense structure and stable chemical properties. There are also a large number of body-centered tetragonal γ'' phase, face-centered cubic γ' phase, and metal carbides dispersed in the superalloy[19], which can greatly improve the yield strength. Meanwhile, austenite has good plasticity, which makes the grinding deformation power and grinding difficulty increase.

Table 1 Chemical composition of GH4169 nickel-based superalloys

Element	C	Cr	Ni	Mo	Ti	Fe	Nb	Mn	Si	Other
Content (%)	≤0.08	20	52	2.9	0.95	-	5.1	0.35	0.35	14-20

Table 2 Physical and mechanical properties of GH4169 nickel-based superalloys

Parameters	Value
Density (kg/m^3)	8240
Melting point ($^{\circ}\text{C}$)	1280
Thermal conductivity ($\text{W/m} \cdot \text{K}$)	17.58
Tensile strength (N/mm^2)	965
Yield strength (N/mm^2)	550
Brinell hardness HB (N/mm^2)	385

According to the hydrodynamic theory of aero-engine compressor blade, the force at the blade tip has a greater impact on the performance of the entire compressor, the shape of the blade tip also affects the aerodynamic performance and noise of the blade. Therefore, the stator blades of the aero-engine compressor are designed as the shape shown in Fig. 1. The length of the blade is 45.0 mm and the maximum thickness is 1.5 mm.

Fig.1. Stator blade model.

Fig.2. The dynamic model of blade tip grinding process.

Since the blade can be seen as a thin-walled part, the motion of the blade in the horizontal direction is much greater than that in the vertical direction during the grinding process, thus the motion of the blade in the vertical direction is ignored. The motion equation of the grinding process is expressed as

$$\begin{cases} m_1 \ddot{x}_1 + c_1 \dot{x}_1 + k_1 x_1 = F_y \\ m_1 \ddot{x}_2 + c_2 \dot{x}_2 + (k + k_2)x_2 + kx_3 = F_x \\ m_2 \ddot{x}_3 + c_3 \dot{x}_3 + (k + k_3)x_3 + kx_2 = 0 \end{cases} \quad (1)$$

$$k = \frac{k_c \bullet k_g}{k_c + k_g} \quad (2)$$

where k_g is grinding stiffness, k_c is contact stiffness, k_1 and k_2 are the equivalent stiffnesses of the grinding wheel in the vertical and horizontal directions, respectively. k_3 is the equivalent stiffness of the workpiece in the horizontal direction. c_1 and c_2 are the equivalent damping of the system in the vertical and horizontal directions, respectively. c_3 is the equivalent damping of the workpiece in the horizontal direction. x_1 and x_2 are absolute displacements of grinding wheel in vertical and horizontal directions, respectively. x_3 is the vibration deflection of the blade tip in the horizontal direction. m_1 and m_2 are the masses of the grinding wheel and the workpiece respectively.

Eq.(1) can be transformed into Laplace domain format, x_1 and x_3 are expressed

as:

$$\begin{cases} x_1(s) = \frac{M \omega^2 \sin \omega t}{m_1 s^2 + c_1 s + k_1} \\ x_3(s) = \frac{-k M \omega^2 \cos \omega t}{(m_2 s^2 + c_3 s + k + k_3)(m_1 s^2 + c_2 s + k + k_2) - k^2} \end{cases} \quad (3)$$

Eq.(3) is transformed into a time-domain function as shown in Eq. (4). Since the equation of $x_3(t)$ is too complex, a series of parameters related to mass, stiffness, and damping are expressed by a constant coefficient (p).

$$\begin{cases} x_1(t) = \frac{2M \omega^2 \sin \omega t}{\sqrt{4k_1 m_1 - c_1^2}} e^{-\frac{c_1}{2m_1} t} \sin\left(\frac{\sqrt{4k_1 m_1 - c_1^2}}{2m_1} t\right) \\ x_3(t) = p M \omega^2 \cos \omega t \end{cases} \quad (4)$$

It can be seen from $x_3(t)$ that the motion of the blade tip should be simple harmonic vibration. Besides, the greater the unbalance of the grinding wheel, the greater the amplitude of the blade tip. The grinding depth will change under the effect of blade vibration and wheel run out. The grinding depth can be expressed as:

$$a_p(t) = a_p + x_1(t) + (l - \sqrt{l^2 - x_3(t)^2}) \quad (5)$$

where a_p is the given grinding depth, and l is the distance from the tip of the blade to the support surface of the workpiece fixture.

2.2 Grinding force modeling

To investigate the vibration mechanism of the grinding process, the grinding force needs to be obtained firstly. Thus a mechanical model was developed to predict grinding force for cutting regime, as shown in Fig.3. F_x , F_y , and F_z represent the grinding forces acting on the blade tip in X, Y, and Z directions, respectively.

$$F = \sqrt{F_x^2 + F_y^2} = M \omega^2 \quad (6)$$

$$F_x = F \cos \omega t \quad (7)$$

$$F_y = F \sin \omega t \quad (8)$$

where F is the vibration force caused by the imbalance of the grinding wheel, and F_x and F_y are the components of the vibration force F . M is an unbalanced amount of grinding wheel system while ω is the vibration acceleration

According to the composition and decomposition of the forces, the grinding force F can be separated into the tangential grinding force F_t , the radial (normal) grinding force F_r , and the axial grinding force F_a as follows:

$$F_t = F_y \quad (9)$$

$$F_r = F_z \sin \omega t - F_x \cos \omega t \quad (10)$$

$$F_a = F_z \cos \omega t - F_x \sin \omega t \quad (11)$$

The grinding force ratio γ is a numerical value that reflects the difficulty of the abrasive grains cutting into the material during the grinding process. The smaller grinding force ratio, the more difficult for the abrasive grains to be cut. The grinding force ratio can be expressed as the average normal grinding force to the average tangential grinding force as shown in equation (12):

$$\gamma = \frac{F_r}{F_t} = \frac{F_z \sin \omega t - F_x \cos \omega t}{F_y} \quad (12)$$

Fig.3. Grinding force model.

3 Machining experiment and scheme

3.1. Experiment equipment

The blade tip was ground with an MGK 7120 surface grinding machine tool as shown in Fig.4. The feed system of the machine tool can realize three-axis linkage. The minimum grinding depth is $0.1 \mu\text{m}$ while table feed rate is 0.3m/min - 25m/min . The grinding wheel is made of CBN, metal bond as shown in Fig.5. The outer diameter is 66.8mm , inner diameter 32mm , width 25mm , the thickness of the abrasive layer is 0.095mm , and the number of abrasive grains is 200-230# (particle size $61\text{-}75 \mu\text{m}$). Besides, the grinding forces were measured by the KISTLER 9272 dynamometer.

Fig.4. MGK 7120 surface grinding machine tool.

(a) The shape of the grinding wheel (b) Grinding wheel topography

Fig.5 CBN profiling grinding wheel.

3.2 Grinding vibration test of the blade tip

The Belgian LMS vibrometer and PCB 356A16 three-directional acceleration sensor (sensitivity 100 mV/g) were used for grinding vibration signal detection as shown in Fig.6. The sensor was fixed on the blade with a miniature magnetic base (Fig.6(b)). It should be emphasized that the direction of the sensor coordinate system should be unified with the machine tool coordinate system.

(a) LMS vibrometer

(b) Vibration measurement site

Fig.6. Vibration measurement system.

According to the hammering experiments on the blade system, the first 5 natural frequency characteristics of the workpiece without hard damping blocks were obtained as shown in Table 3.

Table 3 Intrinsic characteristics of workpieces without hard damping block.

Order	Frequency (Hz)	Damping ratio (%)
1	232.758	0.99
2	349.210	1.49
3	380.892	5.27
4	476.371	2.94
5	517.717	3.46

The mechanical vibration can be categorized into three types: free vibration, forced vibration, and self-excited vibration. To observe the cause of vibration of the blade tip during the grinding process, the analysis flow chart is established as shown in Fig.7. It should be emphasized that before the blade tip grinding test, the dynamic and static balance of the grinding wheel rod and fixture has been adjusted, thus the effect of the imbalance of the spindle system on the blade vibration can be ignored.

Fig. 7. Flow chart of analysis of the cause of blade vibration during blade tip grinding.

LMS test lab equipment was used to measure the blade vibration acceleration during the blade tip grinding process with a spindle speed of 3000r/min. The grinding process was carried out in the direction perpendicular to the blade, as shown in Fig.4. To avoid the influence of grinding fluid on blade vibration and damage to the acceleration sensor, the grinding experiments were carried out at dry condition. The frequency spectrum of blade vibration is obtained with the generated excitation force frequency of 50Hz as shown in Fig.8. The vibration frequency of the workpiece is almost the same at different grinding depths. Moreover, the highest frequency peak is about 483hz, which is close to the fourth natural frequency of blade tip as shown in Table 3. . On the other hand, relatively small frequency peaks appear at 50.08 Hz and 240 Hz. Frequency peaks appear at 50.08 Hz is close to the excitation force-frequency, indicating that the blade tip was got forced vibration. While the frequency peaks appear at 240 Hz is close to the first natural frequency of the blade tip, which shows that there are both forced vibration and self-excited vibration during the grinding process. However, due to the small frequency peak, forced vibration is not the main cause of blade vibration.

Fig. 8. Blade tip vibration frequency spectrum at different grinding depths

According to the analysis in Section 2.1, the main reason that causes blade vibration is the instability of grinding. Grinding instability is manifested in the dynamic change of grinding depth and grinding force, which is mainly caused by the imbalance of the grinding wheel. Nevertheless, the imbalance of the grinding wheel is mainly due to the misalignment of the grinding wheel and the wheel shaft, or the eccentricity of the grinding wheel caused by the undressing.

3.3 Grinding force test and analysis

Table 4 shows the grinding forces measured by KISTLER 9272 dynamometer under different grinding parameters. It can be seen that the normal grinding force and

the tangential grinding force increase to a certain extent with the increase of feed rate and grinding depth, which is attributed to the increase in feed rate and grinding depth, the maximum undeformed chip thickness, and the grinding force of single grain increase. Meanwhile, the increase of the grinding depth will also lead to the increase of the length of the grinding arc, so that the number of effective dynamic abrasive particles involved in grinding will also increase. In addition, the grinding force ratio also increases with the increase of feed rate and grinding depth, however its value is recorded between 1.45 and 1.50, which is not very large[20]. This is mainly because the nickel-based alloy is difficult to cut material and the blade is a thin-walled part, material characteristics and the deflection deformation of the blade make abrasive particles difficult to cut into the material. Moreover, under dry grinding conditions, the friction factor between abrasive particles and workpiece surface is large, resulting in a large tangential grinding force.

Tabel 4 Average grinding force under different grinding parameters.

NO.	spindle speed (rpm)	grinding depth (μm)	feed rate (m/min)	Average tangential grinding force (N)	Average normal grinding force (N)	grinding force ratio
1	3000	3	4.5	12.55	18.21	1.45
2	3000	6	4.5	19.97	29.3	1.467
3	3000	9	4.5	26.38	38.48	1.458
4	3000	12	4.5	37.52	55.66	1.483
5	3000	10	3.5	22.34	30.48	1.364
6	3000	10	6.5	26.64	36.63	1.375
7	3000	10	11.5	27.31	39.65	1.45
8	3000	10	15.5	28.99	43.49	1.50

Fig.9 shows the variation of average grinding force under different grinding parameters. It can be seen from the slope in the figure that the grinding depth has a greater influence on the grinding force than the feed rate. Therefore, it is better to reduce the grinding force by reducing the grinding depth.

Fig. 9. Variation of average grinding force under different grinding parameters.

3.4 Surface quality analysis

For the grinding process, surface roughness is one of the main indicators used to quantitatively characterize the quality of the machined surface, and it is also an important indicator for judging whether the blade meets the processing requirements [21]. Surface roughness refers to the micro geometric features on the machined surface, which are composed of small spacing and valley peaks. However, it has a great influence on the service performance of parts. According to GB/T1031-2009 standard[22], the contour arithmetic square deviation R_a is used to characterize the height characteristics of the surface roughness, which is the arithmetic mean of the absolute value of the ordinate $Z(x)$ within a sampling length, namely:

$$Ra = \frac{1}{l_a} \int_0^{l_a} |Z(x)| dx \quad (13)$$

where l_a is the sampling length.

The grinding process is a complex dynamic system, and grinding vibration has a great influence on the grinding process. In this paper, the dynamic change of grinding depth a_p is used as a bridge to establish a theoretical model of the relationship between blade vibration and blade tip surface roughness. Since the important factor that causes the uneven machining surface is the dynamic change of grinding depth. When the height difference between the abrasive grains is ignored, the height difference of the blade tip surface can be seen as the relative vibration displacement between the workpiece surface and the grinding wheel. It should be emphasized that the sampling length direction of R_a is perpendicular to the grinding feed direction, then:

$$Z(x) = \Delta a_p \quad (14)$$

$$Ra = \frac{1}{l_a} \int_0^{l_a} |a_p| dx = \frac{1}{l_a} \int_0^{l_a} |x_1 + (l - \sqrt{l^2 - x_3^2})| dx \quad (15)$$

According to the dynamic analysis in Section 2.1, Increasing damping can suppress vibration to a certain extent. To explore the practical effect of damping on machining vibration of the blade tip. A hard damping block made of nylon material was manufactured as shown in Fig.10. To facilitate the adjustment of the installation angle and tightness of the damping block, the upper and lower slots of the damping block are designed vertically.

Fig.10. Grinding of blade tip with damping block.

To investigate the influence of damping, grinding depth, and feed rate on the

machined surface roughness of the blade tip, a JB-5C precision roughness tester was used to measure the surface roughness R_a as shown in Fig.11.

Fig.11. Surface roughness measurement.

In the experiment, it is found that the surface roughness of the blade tip is different in the direction perpendicular to the grinding process. Thus, the blade tip surface is divided into three areas based on the test results, as shown in Fig.12, Zone I is the wheel entry area, Zone II is the intermediate area, and Zone III is the wheel exit area. The surface roughness R_a of the three areas in the direction perpendicular to the grinding scratch was measured. Each area was measured 3 times, and the average value was obtained as shown in Table 5.

Fig.12. Division of tip surface area.

Table 5 Effect of processing conditions on surface roughness.

NO.	Grinding depth(μm)	Feed rate (m/min)	Damping block	Surface roughness(μm)			Average (μm)
				1	2	3	
1	5	5.5	No	2.779	2.307	2.687	2.591
2	5	5.5	Yes	2.754	2.327	2.401	2.494
3	10	5.5	No	3.106	2.639	2.828	2.857
4	10	5.5	Yes	3.046	2.566	2.615	2.742
5	15	5.5	No	3.512	2.953	3.219	3.228
6	15	5.5	Yes	3.324	2.831	2.990	3.048
7	20	5.5	No	3.926	3.063	3.412	3.467
8	20	5.5	Yes	3.546	2.900	3.110	3.185
9	10	2.5	No	2.924	2.490	2.774	2.729
10	10	2.5	Yes	2.912	2.447	2.529	2.629
11	10	9.5	No	3.167	2.639	2.828	2.878
12	10	9.5	Yes	3.129	2.694	2.756	2.859

13	10	14.5	No	3.346	2.870	3.064	3.093
14	10	14.5	Yes	3.279	2.818	2.973	3.023
15	10	17.5	No	3.622	3.002	3.203	3.275
16	10	17.5	Yes	3.531	2.903	3.122	3.185

The variation of the surface roughness of the blade tip with grinding depth and feed rate with and without the damping block were obtained as shown in Fig.13. It can be seen that the surface roughness increases with the increase of grinding depth or feed rate, and the surface roughness can be effectively reduced by using the damping block, especially when the grinding depth more than 15 μm . This behavior can be explained as when the grinding depth and feed rate increase, the grinding force increases in which they intensify the vibration of the thin-walled workpiece. By using the damping block, the damping coefficient of the workpiece-fixtured system can be changed, thereby reducing blade vibration and improving the surface roughness of blade tip.

Fig. 13. Variation of surface roughness under different machining conditions.

The VHX5000 super-depth-of-field microscope was used to observe the machined surface morphology of the blade tip as shown in Fig. 14-15. It is obvious that more serious the scratch of abrasive particles, and the more uneven (or irregular) the surface texture at higher grinding depth and feed rate.

According to Eq. (15), the surface roughness of the blade tip is not only related to the sampling length but also related to the vibration displacement x_1 of the grinding wheel, the vibration x_3 of the blade tip, and the overhanging length l of the blade. As the grinding depth increases, the number and contact area of abrasive involved in processing increase, and the vibration of blade tip x_3 increases resulting in more serious scratches. The increase in the feed rate produces a shorter grinding contact time, which in turn increases the surface roughness. In addition, the grinding heat will soften the surface of the workpiece, and the plasticity of the material will increase after heating. During the grinding process of the nickel-based alloy blade tip, the material is locally heated and expands in the direction of the gap around the abrasive grain after being pressed. Meanwhile, the material along the grinding direction will be removed, resulting in the formation of new tiny groove marks on the surface of the workpiece.

Fig. 14. Surface morphology of blade tip under different grinding depths.

Fig. 15. Surface morphology of blade tip at different feed rates.

4 Discussion

4.1 Analysis of grinding vibration on surface roughness

To further study the relationship between vibration and surface roughness of the blade tip, an experiment was carried out to obtain the vibration acceleration and the surface roughness R_a as shown in Table 6. It can be seen that under the fixed feed rate

and spindle speed, when the grinding depth is less than $1\mu\text{m}$, the vibration acceleration of the blade is still relatively small, and the maximum value is only 1.68g . on the other hand, with the increase of grinding depth, the vibration acceleration of blade increases sharply, especially when the grinding depth increases from $1\mu\text{m}$ to $2\mu\text{m}$ and from $4\mu\text{m}$ to $5\mu\text{m}$, the vibration acceleration increases by 13.54g and 29.88g , respectively. When the grinding depth increases from $2\mu\text{m}$ to $4\mu\text{m}$, the vibration acceleration increases uniformly, about $7\text{g}/\mu\text{m}$. This attitude can be explained as when the grinding depth is below $1\mu\text{m}$, the actual number of abrasive particles involved in the grinding and the grinding force are relatively low, which has a small impact on the machining quality. Notwithstanding, when the grinding depth gradually increases from $1\mu\text{m}$ to $2\mu\text{m}$, the number of abrasive particles involved in the grinding gradually increases, resulting in a significant increase of the grinding force. Meanwhile, when the grinding depth continues to increase from $2\mu\text{m}$ to $4\mu\text{m}$, the number of abrasive particles remains constant. However, the contact area between the abrasive particles and the workpiece increases uniformly, resulting in a uniform increase of the grinding force. When the grinding depth exceeds $4\mu\text{m}$, the grinding depth exceeds the height of the part of the abrasive particles causing direct contact between the substrate and the workpiece and a rapid increase of the grinding force. In addition, when the grinding wheel close to the blade before grinding, the blade has a very small vibration. This is mainly due to the high-speed airflow generated by the high-speed rotation of the grinding wheel, which causes the blade to vibrate. At the same time, vibration in the operation of the machine tool will aggravate the vibration of the blade.

The reasons for the obvious grinding vibration can be listed as follow:

1)With the increase of grinding depth, the thickness and width of a single abrasive cutting edge participating in cutting are gradually increased, so the contact area between the grinding wheel and the workpiece is increased. Furthermore, the number of effective abrasive is also increasing, resulting in the synchronous increase of grinding force and grinding vibration.

2) When the grinding wheel contact with the workpiece, in the beginning, there is only sliding friction without grinding effect with a negligible, vibration. With the increase of grinding depth, the material removal mode changes from sliding friction to ploughing and grinding, while the corresponding grinding vibration also increases.

3)With the increase of grinding depth, the grinding area of the workpiece is insufficiently cooled, and the heat accumulation of grinding will cause "thermal softening" of the contact area between the abrasive particles and the workpiece, which causes the material damage due to loss of stability. Besides, the grinding vibration increase.

Table 6 Single-factor experiment of blade vibration acceleration and surface roughness.

NO.	Grinding depth (μm)	Feed rate (m/min)	Maximum vibration acceleration (g)	Surface roughness (μm)		
				Zone I	ZoneII	Zone III
1	0	3.5	0.51	1.041	1.040	1.041

2	1	3.5	1.68	1.877	1.725	1.754
3	2	3.5	15.22	2.279	2.186	2.212
4	3	3.5	22.68	2.752	2.551	2.575
5	4	3.5	29.16	3.181	2.605	2.704
6	5	3.5	59.04	3.339	3.173	3.253

Fig. 16. The relationship between vibration and surface roughness.

From Fig.16, it can be seen that under vibration acceleration of 1.68g (grinding depth of 1 μm), surface roughness increases sharply with the increase of vibration acceleration. Subsequently, surface roughness increase linearly and steadily with the increase of vibration acceleration in the zone I and zone II, the roughness in area I has a relatively large fluctuation with the increase of acceleration. This reflects that when the grinding depth is less than 1 μm , as the grinding depth increases, the number of effective abrasive particles and the contact area that participate in the grinding increase rapidly, resulting in a rapid increase in vibration acceleration and surface roughness. When the cutting depth exceeds 1 μm , the number of effective abrasive particles that participate in the grinding remains relatively constant, and the vibration acceleration and surface roughness also increase slowly and steadily in the zone I and zone II. However, in the initial contact zone I, due to instantaneous contact between grinding wheel and workpiece, the grinding unstable state is relatively large, which makes the surface roughness in the zone I change greatly.

4.2 Analysis of surface quality difference of blade tip

According to Table 5-6, the variation trend of surface roughness with the grinding depth of the three areas I-III is obtained as shown in Fig.17. There are differences in the surface roughness of the blade tip processing. The surface roughness in the zone I of the entry area is the largest, the exit area zone III is the second largest, and the intermediate area zone III is the smallest. The damping block can reduce the surface roughness of the blade tip processing, however, it did not reduce the degree of difference in surface roughness. Under the condition of a certain feed rate, with the increase of grinding depth, the difference in surface roughness of the three areas also gradually increases, especially when grinding depth is bigger than 4 μm , the surface

roughness difference increases significantly. This is mainly due to the increased blade vibration. under the condition of a certain grinding depth (such as $10\mu\text{m}$), as the feed rate increases, the surface roughness of the blade tip also increase, but the difference of surface roughness of the three areas is very small, which means the feed rate has little effect on the difference of the surface roughness.

Fig. 17. The relationship between grinding depth and surface roughness.

Many factors affect the machining surface quality of the blade tip, but under the same processing conditions, the difference in the surface quality of the blade tip may be caused by the vibration. To explore this problem, the blade vibration acceleration-time change status was measured by using the LMS test. lab under the machining parameters with a feed rate of 3.5m/min , grinding depth of $1\mu\text{m}$, $2\mu\text{m}$, $3\mu\text{m}$, $4\mu\text{m}$, and $5\mu\text{m}$, respectively, without damping block, as shown in Fig.18. The small peaks in Fig.18(a) are due to the sudden turning movement of the table, which causes a vibration acceleration of the blade. Since the maximum thickness of the tip is 1.5mm , the thickness of each area where the tip surface is divided into three equal parts is 0.5mm , as shown in Fig.12. Thus The vibration acceleration-time curve in one grinding cycle is shown in Fig.19. It can be seen that when the grinding wheel enters zone I, the vibration acceleration of the blade is the largest, which means when the grinding wheel contacts the blade tip at the beginning, the instantaneous vibration is the largest, resulting in a large difference in the removal of the material, and the corresponding surface roughness is the largest. When the grinding wheel enters zone II, the vibration acceleration of the blade decreases, which is because the supporting point is existed in the center of the blade, and the moment of zone II is small. Therefore, under the same elastic modulus and stiffness, the deformation of zone II is the smallest.

(a) $v_w=3.5\text{m/min}$, $a_p=1\mu\text{m}$

(b) $v_w=3.5\text{m/min}$, $a_p=2\mu\text{m}$

(c) $v_w=3.5\text{m/min}$, $a_p=3\mu\text{m}$

(d) $v_w=3.5\text{m/min}$, $a_p=4\mu\text{m}$

(e) $v_w=3.5\text{m/min}$, $a_p=5\mu\text{m}$

Fig. 18. Vibration acceleration-time curve of blade tip.

(a) $v_w=3.5\text{m/min}$, $a_p=1\mu\text{m}$

(b) $v_w=3.5\text{m/min}$, $a_p=2\mu\text{m}$

Fig. 19. The vibration acceleration-time curve of blade tip in one grinding cycle.

As shown in Fig.19, it can be seen that there is an obvious sudden acceleration point in the vibration acceleration curve in the second half of zone III, which is because the contact arc length sudden change when the grinding wheel leaves the blade tip as shown in Fig. 6. Additionally, the blade is subject to tangential grinding force and deforms in the direction away from the grinding wheel, increasing the contact arc length between the abrasive grains of the grinding wheel and the blade tip. When the grinding wheel starts to leave the tip of the blade, the length of the contact arc suddenly decreases until disappears, which makes the surface roughness increase. When the grinding wheel is completely separated from the blade tip, the vibration acceleration still exists, as the result of the vibration of the blade. It can be seen from the blade vibration acceleration curve in Fig.19(a) that when the blade tip grinding depth is $1\mu\text{m}$, the blade has obvious vibration acceleration only when the grinding wheel contacts the blade tip at the beginning. Nevertheless, the vibration acceleration of the blade is not obvious, which indicates that the blade vibration is very small in the grinding process. Therefore, to reduce the vibration during the grinding of the blade tip and reduce the surface quality differentiation characteristics, the grinding depth should not exceed $1\mu\text{m}$ with no extra damping.

5. Conclusion

In this paper, the vibration characteristics of GH4169 nickel-based superalloy

blade tip in grinding and its influence on machined surface quality are studied, the conclusions which obtained through the study can be drawn as follow:

1. The vibration in blade tip grinding and the resulting non-linear change of grinding depth will reduce the surface quality of blade tip machining, and cause the difference in surface quality in different areas of the blade tip.

2. When the grinding wheel contacts to the blade tip, at the beginning, the vibration acceleration of the blade is the largest, resulting in the largest surface roughness in the entering zone. After the grinding wheel enters the intermediate zone, the blade vibration and the surface roughness are reduced. When the grinding wheel leaves the tip, the blade vibration is reduced, However, the sudden change of vibration caused by the change of contact arc length leads to the increase of the surface roughness.

3. Grinding depth has a great influence on the surface quality difference of blade tip, especially when the grinding depth is greater than 4 μ m. The surface roughness difference increases obviously. The feed rate has little effect on the surface quality difference of the blade tip.

4. Adding a damping block can reduce the surface roughness of the blade tip, however, it does not reduce the difference in surface quality.

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Declarations

-Ethical Approval: Not applicable

-Consent to Participate: Not applicable

-Consent to Publish: Not applicable

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-Availability of data and materials: Some or all data generated or used during the study are available from the corresponding author by request.

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