Study on the characteristics of high temperature alloy surface profile grinding process

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Abstract

High-temperature alloy profile grinding is mainly used in the machining of aero-engine turbine structural parts, which require high surface quality and high machining efficiency. However, the process ability of machining high-temperature alloys is poor. For this reason, this paper conducts experimental research on the surface profile grinding process of high-temperature alloys to meet the surface quality and machining efficiency requirements of high-temperature alloy structural parts.

Using a precision profile grinding machine, WA and SG grinding wheels are selected for profile grinding tests on three types of workpieces with curved surfaces: flat, convex, and concave. Each shape of the workpiece was shaped-ground using WA and SG grinding wheels separately. The orthogonal experimental method was used to perform profile grinding by changing three factors: grinding wheel speed, feed, and backlash. The surface roughness after grinding was measured and compared, and the most suitable process parameters for grinding three curved workpieces with WA and SG grinding wheels were obtained by comparing the surface quality and machining efficiency. The grinding strategy is also given for surface roughness and machining efficiency. It provides a basis for the improvement of the quality and efficiency of high-temperature alloy forming and grinding.

1. Introduction

Nickel-based alloys are the most widely used and high-temperature strength class of high-temperature alloys and are typically difficult to machine materials [1]. Form grinding is the process of dressing the grinding wheel to produce a counter shape that exactly matches the workpiece profile, and using this dressing to obtain a specific shape to grind the workpiece, thereby achieving the required shape of the workpiece [2].

Nickel-based alloys have been widely used in the aerospace field in recent years. The application objects of the nickel-based high-temperature alloy profile grinding process are mainly structural parts of the turbine part of the aero-engine, such as turbine rotor blade tenons and teeth, turbine disk tenons, and grooves, high-pressure turbine guides, high-pressure turbine outer rings, etc [3, 4]. The actual production applications have the same machining requirements for these structural parts, i.e., high surface quality, high contour accuracy, and high machining efficiency.

The poor machining process performance of nickel-based high-temperature alloys under ordinary grinding conditions [5, 6] is due to the high yield strength of nickel-based alloys, which consumes a lot of energy in the process of material removal; the low thermal conductivity of nickel-based alloys makes it easier for the large amount of heat generated in the process of material removal to gather and form local high temperatures, resulting in burns or cracks on the surface of the machined workpiece, which eventually leads to the machined workpiece, ultimately leading to the poor surface quality of the machined workpiece and making it difficult to meet machining requirements [7, 8]. According to the grading characteristics of nickel-based alloys, scholars at home and abroad have mainly studied them in two aspects: first, developing advanced grinding equipment and tools and processes, as well as adopting various ways to enhance the grinding capacity of grinding wheels and
improve the removal rate and surface integrity level of nickel-based alloy materials; second, studying the influence of material characteristics, cooling characteristics, machine tool characteristics, grinding wheel parameters, dressing parameters, and grinding parameters on nickel-based alloy materials [9–11].

This paper conducts an experimental study on the surface profile grinding process of high-temperature alloys. Using a precision profile grinding machine, grinding tests are conducted for flat, convex, and concave workpieces using the orthogonal experiment method to study the effects of grinding wheel speed, workpiece feed, and grinding depth on the surface roughness of the workpieces during grinding, and to provide a basis for improving the surface quality of grinding of difficult-to-process materials.

### 2. High-temperature alloy surface profile grinding process characteristics

The material properties of high-temperature alloys determine that they are easy to cause grinding wheel adhesion and clogging during grinding, and the grinding force is high and the grinding temperature is high, so the grinding surface quality of high-temperature alloys is not easily guaranteed [12–14]. While grinding high-temperature alloys with diamond wheels, the experimental results showed that the grinding wheels were easy to clog and the grinding burns were serious, so corundum-type grinding wheels were generally used for grinding high-temperature alloys [15].

In grinding, the three elements that affect the surface quality of grinding are: grinding wheel speed $S$, workpiece feed $F$, and grinding depth $a_p$. Surface roughness is an important measure of the surface quality of the grinding process [16]. The smaller the surface roughness value, the better the wear resistance of the machined
part; the smaller the surface roughness value, the fewer the surface defects and the better the fatigue strength of the machined part; the larger the surface roughness value, the worse the corrosion resistance of the machined part; the larger the surface roughness value, the worse the quality of the matching surface. Therefore, the surface roughness value is chosen as the measure of the surface quality of the grinding process [17].

To study the process characteristics of high-temperature alloy profile grinding, two types of specimens, flat and circular curved, were selected. The specimens were milled on a CNC machining center, rough machined to shape, and then tested on a three-coordinate profile grinding machine for profile grinding. The orthogonal experimental method was used because the effects of the three elements of feed F, rotational speed S, and depth of cut \( a_n \) on the surface quality of ground were to be studied. The orthogonal experimental method is an efficient experimental design method for studying multiple factors and levels, which can achieve the optimal combination of levels with a smaller number of experiments [18]. The orthogonal table for the experimental protocol design is shown in table 1.
Table 2. Surface grinding parameters.

| Name                          | Size model          |
|-------------------------------|---------------------|
| Grinding wheel type          | WA (80°)/SG (80°)   |
| Specimen roughness Ra (μm)   | 1.6                 |
| Jet speed (m s⁻¹)             | 1.9                 |
| Jet position                  | lower part          |
| Direction of spraying         | Horizontal to the left |
| Types of grinding fluids      | Water-based         |
| Grinding wheel speed S (r min⁻¹) | 1500/2000/3000     |
| Feed rate F (mm min⁻¹)        | 30/60/100           |
| Grinding depth aₚ (mm)        | 0.002/0.003         |

Figure 4. The value of Ra when S, F, and aₚ are different.
2.1. Test equipment

White corundum (WA) wheels and SG wheels were selected for the test, both with a grit size of 80#, which is commonly used for fine grinding in profile grinding. The wheel dimensions are (OD × thickness × ID) 180 mm × 12.7 mm × 31.75 mm. White corundum (WA) grinding wheels are white in colour, harder than brown corundum, with easily broken abrasive grains, sharp edges, good cutting performance and low grinding heat, suitable for grinding quenched steel, alloy steel, high-speed steel, high-carbon steel and thin-walled parts [19]. SG grinding wheels have the advantages of good wear resistance, low grinding heat, long service life, high removal rate, large grinding ratio G (ratio of volume of material ground to volume consumed by the grinding wheel) and good grinding quality [20]. The two types of grinding wheels are shown in figures 1 and 2.

The grinding machine selected for the test was the Mitsui Super Precision Surface Grinder (MSG-618PC-NC), as shown in figure 3. The grinding machine has a spindle rotation of 60 Hz, a minimum feed depth of 0.1 μm up and down, a table working surface size of 480 × 150 mm and an operating power of 6 KVA.

After each grinding wheel test is completed, the roughness of the machined workpiece surface is measured using the SJ-210 surface roughness measuring instrument.

![Figure 5. The value of Ra when S, F, and ap are different.](image-url)
2.2. Test material
The material selected for the test is a nickel-based high temperature alloy (GH416) which, for special performance requirements, contains, in addition to the base element nickel, strengthening elements such as Cr, Fe, Mo, Co, Nb, Al, Ti, etc [21]. The mass fractions (%) of each element are: Cr 17–21, Mo 2.8–3.3, Co 1.0, Nb 5.25, Al 0.91, Ti 0.96 and the balance of Fe [22].

2.3. Test programme
The workpiece was subjected to reciprocating grinding experiments using white corundum and SG grinding wheels respectively, and the experimental parameters for flat grinding were designed as shown in table 2.

3. Test results and analysis

3.1. High temperature alloy surface grinding process characteristics
3.1.1. SG (80#) grinding wheels were selected and the test results are shown in table 3 and figure 4.
3.1.1.1. Discussion
From figures 4(a) and (b), it can be seen that when the grinding wheel speed is lower than 2000 r min$^{-1}$, the grinding depth is too large, causing the surface roughness of the workpiece to become larger. Moreover, under the same grinding depth and feed, increasing the grinding wheel speed can generally improve the grinding quality, while when the grinding wheel speed is higher than 2000 r min$^{-1}$, increasing the grinding wheel speed will reduce the surface quality of the workpiece while keeping the feed and grinding depth constant. From figures 4(b) and (c), it can be seen that when the grinding wheel speed is 2000 r min$^{-1}$, a medium feed and small grinding depth can give a better surface quality, while when the grinding wheel speed is 3000 r min$^{-1}$, it is just the opposite.

It can be seen that when using SG (80#) grinding wheels, to ensure roughness while taking into account efficiency, the best surface quality is achieved when the grinding wheel speed S is 2000 r min$^{-1}$, the feed F is 60 mm min$^{-1}$ and the grinding depth ap is 0.002 mm, at which time the surface roughness can reach $Ra = 0.11 \mu m$.

3.1.2. WA (80#) grinding wheels were selected and the test results are shown in figure 5.
3.1.2.1. Discussion
As can be seen from figure 5, the surface roughness of the workpiece tends to decrease with the increase of the grinding wheel speed at a certain feed and grinding depth; when the grinding wheel speed reaches 3000 r min$^{-1}$, the surface roughness value reaches the lowest and the workpiece surface quality is the best. From figure 5(c), it can be seen that when the grinding wheel speed is 3000 r min$^{-1}$ and the grinding depth is certain, increasing the feed, the surface roughness of the workpiece shows a low value at a medium feed, and the surface quality of the workpiece is better at this time.

When the grinding wheel speed S is 3000 r min$^{-1}$ the feed F is 60 mm and the grinding depth ap is 0.003 mm, the surface quality of the workpiece is best, and the surface roughness is $Ra = 0.12 \mu m$.
3.2. High-temperature alloy convex curved workpiece profile grinding process characteristics

For profile grinding of convex curved surfaces, a gradual change in speed from medium to low or high speed is used to prevent damage to the tester, the workpiece, or the equipment when the grinding wheel is fed at low or high speeds.

During the test, it was found that when the grinding wheel feed was below 100 mm min\(^{-1}\), increasing the speed or grinding depth would cause serious vibration, resulting in obvious vibration patterns on the surface of the workpiece, as shown in figure 6, which greatly affected the surface quality of the workpiece. Therefore, compared to flat grinding, the grinding parameters in the orthogonal test table were replaced by 100/200/300 mm min\(^{-1}\) in the order of 30/60/100 mm min\(^{-1}\) feed rate for shaped convex arc grinding, and the rest of the grinding parameters were selected as shown in table 4.

### Table 3. Experimental data for surface grinding with SG (80#) grinding wheels.

| Grinding wheel speed S (r min\(^{-1}\)) | Feed rate F (mm min\(^{-1}\)) | Grinding depth a\(_p\) (mm) | Specimen roughness Ra (\(\mu m\)) |
|--------------------------------------|-----------------------------|---------------------------|--------------------------|
| 1500                                 | 30                          | 0.002                     | 0.14                     |
|                                      |                             | 0.003                     | 0.15                     |
|                                      | 60                          | 0.002                     | 0.16                     |
|                                      |                             | 0.003                     | 0.17                     |
|                                      | 100                         | 0.002                     | 0.19                     |
|                                      |                             | 0.003                     | 0.21                     |
| 2000                                 | 30                          | 0.002                     | 0.12                     |
|                                      |                             | 0.003                     | 0.29                     |
|                                      | 60                          | 0.002                     | 0.11                     |
|                                      |                             | 0.003                     | 0.14                     |
|                                      | 100                         | 0.002                     | 0.15                     |
|                                      |                             | 0.003                     | 0.2                      |
| 3000                                 | 30                          | 0.002                     | 0.17                     |
|                                      |                             | 0.003                     | 0.17                     |
|                                      | 60                          | 0.002                     | 0.2                      |
|                                      |                             | 0.003                     | 0.18                     |
|                                      | 100                         | 0.002                     | 0.17                     |
|                                      |                             | 0.003                     | 0.3                      |

### Table 4. Forming convex arc grinding parameters.

| Name                                      | Size model |
|-------------------------------------------|------------|
| Grinding wheel type                       | WA (80#)/SG (80#) |
| Radius of circle (mm)                     | 360        |
| Specimen roughness Ra (\(\mu m\))        | 1.6        |
| Jet speed (m s\(^{-1}\))                 | 1.9        |
| Jet position                              | middle part|
| Direction of spraying                     | Angle of 10\(^{\circ}\) to the horizontal |
| Types of grinding fluids                  | Water-based |
| Grinding wheel speed S (r min\(^{-1}\))  | 1500/2000/3000 |
| Feed rate F (mm min\(^{-1}\))            | 100/200/300 |
| Grinding depth a\(_p\) (mm)              | 0.002/0.003 |

3.2.1. SG (80#) grinding wheels were selected and the test results are shown in figure 7.

During the test, it was found that when the grinding depth was 0.003 mm and the feed rate was increased to 300 mm min\(^{-1}\), the workpiece began to vibrate and produce various degrees of vibrations, which affected the quality of the machined surface, so the surface roughness was not measured at this process parameter and beyond.

### 3.2.1.1. Discussion

From figure 7(a), it can be seen that when the grinding wheel speed is 1500 r min\(^{-1}\), a smaller feed is more beneficial to the surface quality; when the speed is 2000 r min\(^{-1}\), a larger grinding depth is more beneficial to the surface quality of the workpiece; when the speed reaches 3000 r min\(^{-1}\), changing the feed and grinding depth has
a relatively low effect on the surface roughness of the workpiece, and during the actual test, there is a very slight vibration.

Therefore, the use of SG (80#) grinding wheels at a speed S of 2000 r min⁻¹, a feed F of 200 mm min⁻¹, and a depth of cut ap of 0.003 mm gives good grinding quality with a surface roughness of $Ra = 0.38 \mu m$.

3.2.2. WA (80#) grinding wheels were selected and the test results are shown in figure 8. When a WA (80#) grinding wheel was selected for grinding tests on convex arcs, when the feed rate was 100 mm min⁻¹ and the grinding depth was 0.003 mm, the workpiece began to produce different degrees of vibrations and slight burns, which affected the surface quality of the machining, so the surface roughness under this process parameter was not measured; when the feed rate was 300 mm min⁻¹, changing both the grinding wheel speed and grinding depth caused different degrees of burns, and the surface roughness under this process parameter was not used as a reference.
3.2.2.1. Discussion
As can be seen from figure 8, when the feed is 100 mm min$^{-1}$, increasing the grinding wheel speed reduces the surface roughness of the workpiece; when the feed is 200 mm min$^{-1}$, changing the grinding wheel speed or grinding depth has less effect on the surface roughness of the workpiece. Therefore, when using WA (80#) grinding wheel for convex arc profile grinding, the grinding wheel speed should not be too low, as the workpiece surface is prone to cracking at lower speeds, which is not conducive to workpiece processing.

From the viewpoint of processing efficiency and quality, the recommended grinding wheel speed $S$ is 3000 r min$^{-1}$, the grinding depth $a_p$ is 0.002 mm and the feed rate $F$ is 100 mm min$^{-1}$. The surface roughness is $Ra = 0.13 \mu m$.

3.3. Characteristics of the profile grinding process for high-temperature alloy concave-circular curved workpieces
The concave arc grinding process differs from the convex arc in that the contact arc is longer, the cooling conditions are better and the surface quality of the workpiece is better after machining, but it is more likely to
During the test, it was found that when the grinding wheel feed was below 100 mm min\(^{-1}\), increasing the grinding wheel speed or grinding depth would cause serious vibration, resulting in obvious vibration patterns on the surface of the workpiece; when the grinding wheel speed reached 3000 r min\(^{-1}\), burns of varying degrees occurred at each parameter, which greatly affected the surface quality of the workpiece. Therefore, in comparison with flat grinding, the grinding parameters in the orthogonal test table are replaced by 100/200/300 mm min\(^{-1}\) in the feed rate of 30/60/100 mm min\(^{-1}\) and 2500 r min\(^{-1}\) in the grinding wheel speed of 3000 r min\(^{-1}\), at which time the grinding parameters for forming concave circular arc grinding are selected as shown in table 5.

3.3.1. SG (80#) grinding wheels were selected and the test results are shown in figure 10.

When SG (80#) was selected for the grinding test, it was found that when the grinding depth was 0.003 mm, the surface of the workpiece was prone to burns and vibrations, which was detrimental to the surface quality of the workpiece and easily caused damage to the workpiece, grinding wheel and machine tool, as shown in figure 9. Therefore, only the surface roughness at a grinding depth of 0.002 mm was measured when the SG (80#) wheel was used for profile grinding of concave arcs.

3.3.1.1. Discussion

From figure 10(a) it can be seen that when the grinding wheel speed is 1500 r min\(^{-1}\), with the increase in feed, the surface roughness of the workpiece is reduced and then increased, that is, the best surface quality at medium feed; compare figures 10(b), (c) it can be seen that when the grinding wheel speed is greater than 2000 r min\(^{-1}\), lower feed is more conducive to the surface quality of the workpiece.

Therefore, to ensure processing efficiency while taking into account the surface quality of the workpiece, the grinding wheel speed S is chosen to be 2500 r min\(^{-1}\), the feed F is chosen to be 200 mm min\(^{-1}\) and the grinding depth \(a_p\) is chosen to be 0.002 mm in favor of concave arc grinding, at which time the surface roughness is \(Ra = 0.11 \mu m\).

### Table 5. Forming concave arc grinding parameters.

| Name                                | Size model                      |
|-------------------------------------|----------------------------------|
| Grinding wheel type                 | WA (80#)/SG (80#)                |
| Radius of circle (mm)               | 390                              |
| Specimen roughness \(Ra (\mu m)\)   | 1.6                              |
| Jet speed (m s\(^{-1}\))            | 1.6                              |
| Jet position                        | Upper part                       |
| Direction of spraying                | Angle of 10° to the horizontal   |
| Types of grinding fluids            | Water-based                      |
| Grinding wheel speed \(S \text{ (r min\(^{-1}\)}\) | 1500/2000/2500                   |
| Feed rate \(F \text{ (mm min\(^{-1}\)}\) | 100/200/300                      |
| Grinding depth \(a_p \text{ (mm)}\) | 0.002/0.003                      |

Figure 9. When grinding depth is 0.003, concave arc surface burns and seismic marks.
3.3.2. WA (80#) grinding wheels were selected and the test results are shown in figure 11. When a WA (80#) grinding wheel was selected for the grinding test, the surface of the workpiece was burned to varying degrees when the feed was 300 mm min$^{-1}$ and the grinding wheel speed was too low or too high; when the grinding wheel speed was 2000 r min$^{-1}$ and the grinding depth was 0.002 mm, the surface of the workpiece showed slight vibrations, so the surface roughness of the workpiece was not measured under this process parameter.

3.3.2.1. Discussion

From figure 11(a), it can be seen that when the grinding wheel speed is 1500 r min$^{-1}$, increasing the feed or grinding depth will improve the surface quality of the workpiece; from figure 11(b), it can be seen that when the grinding wheel speed is 2000 r min$^{-1}$, the surface roughness of the workpiece increases with the feed, i.e. a smaller feed at this wheel speed is more beneficial to the surface quality of the workpiece; from figure 11(c), it can be seen that when the grinding wheel speed is 2500 r min$^{-1}$, the surface roughness of the workpiece at medium feed is lower and the surface quality of the workpiece is better.
From the above analysis, it can be seen that to ensure the processing speed and the surface quality of the workpiece, the optimal grinding parameters are the grinding wheel speed $S$ of 2500 r min$^{-1}$, the feed $F$ of 200 mm min$^{-1}$, and the grinding depth $a_p$ of 0.002 mm when the WA (80#) grinding wheel is used to grind the concave arc, and the surface roughness is $Ra = 0.07 \mu m$.

4. Conclusions

Using a precision profile grinding machine, a selection of WA and SG wheels are used for profile grinding tests on three curved workpiece shapes: flat, convex, and concave. Each workpiece is profiled ground with WA and SG wheel. The surface roughness is measured and analyzed in comparison to the surface quality and machining efficiency to determine the most suitable process parameters for grinding the three curved workpieces with each wheel.

The orthogonal test method was used to control the three process parameters of grinding wheel speed $S$, workpiece feed $F$, and grinding depth $a_p$ for profile grinding experiments, and the following conclusions were obtained by analyzing the experimental data.
(1) For flat workpieces, the surface quality is better when the feed of the SG grinding wheel (80#) is \( F = 60 \text{ mm min}^{-1} \), the grinding wheel speed \( S = 2000 \text{ r min}^{-1} \), and the grinding depth \( a_p = 0.002 \text{ mm} \); the surface quality is better when the feed of WA grinding wheel (80#) is \( F = 60 \text{ mm min}^{-1} \), the grinding wheel speed \( S = 3000 \text{ r min}^{-1} \) and the grinding depth \( a_p = 0.003 \). The surface quality is better.

If you are looking for surface roughness, use SG wheels with \( S = 2000 \text{ r min}^{-1} \), \( F = 60 \text{ mm min}^{-1} \), \( a_p = 0.002 \text{ mm} \), and \( Ra = 0.11 \mu \text{m} \). If you want to combine efficiency with surface roughness, use WA wheels with \( S = 3000 \text{ r min}^{-1} \), \( F = 60 \text{ mm min}^{-1} \), \( a_p = 0.003 \text{ mm} \), when \( Ra = 0.12 \mu \text{m} \).

(2) For convex arc workpieces, comparing SG (80#) and WA (80#), it is found that the surface quality of the workpiece is better when using WA, but the feed and grinding depth should not be too large when using WA, otherwise, it will easily cause surface burns or shock lines on the workpiece, so if you want to obtain a better surface quality, you can carry out multiple fine grinding.

The use of SG (80#) grinding wheels at a speed \( S = 2000 \text{ r min}^{-1} \), a feed \( F = 200 \text{ mm min}^{-1} \) and a depth of cut \( a_p = 0.003 \text{ mm} \) gives better grinding quality, at which time \( Ra = 0.38 \mu \text{m} \); however, in terms of processing efficiency and quality, it is recommended that the speed of the WA grinding wheel \( S = 3000 \text{ r min}^{-1} \), the grinding depth \( a_p = 0.002 \text{ mm} \) and the feed \( F = 100 \text{ mm min}^{-1} \) when \( Ra = 0.13 \mu \text{m} \).

(3) For concave circular workpieces, good surface quality can be obtained when grinding with both wheels. The surface quality is better when the WA wheel feed rate \( F = 200 \text{ mm min}^{-1} \), speed \( S = 2500 \text{ r min}^{-1} \), and grinding depth \( a_p = 0.002 \text{ mm} \), which can reach \( Ra = 0.07 \mu \text{m} \).

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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