Study on chip formation in grinding of nickel-based polycrystalline superalloy GH4169

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Abstract
Based on the variation of the actual cutting depth during the grinding process, a 3D finite element simulation model for grinding nickel-based superalloy GH4169 with single abrasive was initially constructed. Then, the morphological evolution of the grinding chips during the grinding process was studied. In addition, the effect of the single abrasive cutting depth and the grinding speed on chip morphology and segmentation frequency were investigated. Finally, experimental results with the same test parameters verify the finite element simulation results. The results showed that in the experimental grinding speed range, the sawtooth lamellar chip with the free surface being serrated and the contact surface being smooth due to the extrusion of the abrasive are easy to produce when grinding nickel-based superalloy GH4169. As the grinding speed increases, the chip morphology changes from a unitary lamellar chip to a continuous serrated chip, developing into a continuous ribbon chip. The chip segmentation frequency is mainly determined by grinding depth and grinding speed. To be specific, the smaller the grinding depth and the greater the grinding speed, the greater the chip formation frequency.

Keywords Nickel-based superalloy GH4169 · Chip formation · Finite element simulation · Grinding

1 Introduction
Nickel-based superalloys can serve in high-temperature (600~1100 °C) environments and can be subjected to various high-temperature complex cyclic stresses, with excellent high-temperature strength, creep resistance, and corrosion resistance, and have been widely used in aero-engine turbine blades, turbine disks and other core components. However, the excellent physical properties of nickel-based superalloys can lead to various difficulties, such as low machining efficiency, poor surface quality, and high machining costs. A great number of tests and investigations on nickel-based superalloys have been conducted by researchers, with positive results. They intend to enhance the surface quality of workpieces, improve the machining properties of difficult-to-machine materials, and increase machining efficiency.

Gong et al. [1] developed a model for predicting the normal and tangential forces of a nickel-based single crystal superalloy. The authors investigated the impact of grinding parameters on grinding forces, surfaces, and subsurfaces. Miao et al. [2] used alumina grinding wheels to perform trials on several nickel-based superalloys and discovered that the grinding wheel mostly suffered abrasive wear while grinding DZ408, K403, and GH4169, but primarily encountered abrasive clog when grinding DD6. Dai et al. [3, 4] investigated the effect of diamond grain cutting-edge morphology and grinding speed on the machining performance of Inconel 718. Cai et al. [5, 6] evaluated the machining process parameters and performed orthogonal tests on the grinding surface quality of the nickel-based single crystal superalloy DD5. Ding et al. [7] effectively predicted the grinding surface topography by reconstructing the measured surface topography of CBN grinding wheels. Ruzzi et al. [8] evaluated the effect of several grinding parameters on the surface profile of the Inconel 718.

The study of the grinding and removal mechanism of nickel-based alloy materials is of great significance for gaining insight into the grinding and removal process, solving
the grinding and machining challenges of nickel-based superalloys, and obtaining a machined surface quality that meets the design requirements. The essence of grinding is the removal of workpiece material through the synergy between the cutting edges of tens of thousands of tiny abrasive grains on the grinding wheel [9, 10]. Because of the large number of abrasives involved, it is more difficult to study the chip formation pattern of nickel-based superalloys, and it is more difficult to carry out a quantitative analysis. A novel approach of single grain grinding is proposed on a developed grinder at nanoscale depth of cut and 40.2 m/s [11], in which the speeds used are three- to seven-order magnitude higher than those employed in nanoscratching [12]. Force, stress, depth of cut, and size of plastic deformation are calculated at onset of grinding [13]. In addition, a novel model of the maximum undeformed chip thickness is suggested, which is in good agreement with those experimentally [14, 15]. Under the breakthrough of theories, novel diamond wheels and machining approaches are developed [16]. These studies are a great contribution to the traditional grinding and manufacturing [12]. Öpöz and Chen [17–19] looked into the material removal process of single abrasive grinding and discovered that single-edged abrasive is more efficiently removed, while multi-edged abrasive is more likely to plough. Zhao et al. and Chen et al. [20, 21] measured the grinding forces, the maximum undeformed cutting thickness, and the grinding morphology at different speeds. Tian et al. [22] explored the influence of grinding speed on the removal of nickel-based superalloy GH4169 material by the single abrasive test method and studied the critical chip-forming thickness of chip formation. Feng et al. [23] investigated the formation of scratches, chips, and grinding forces during single grain grinding. The influence of grinding parameters on the ground surface of Inconel 625 was analyzed by Ruzzi et al. [24]. They discovered that Inconel 625 is particularly vulnerable to work hardening during the grinding process, with grinding speed having the most significant impact. Li et al. [25] developed a grinding force model based on the single abrasive cutting process and verified the accuracy of the model by orthogonal grinding tests. Denkena et al. [26] proposed a new method to experimentally analyze the mechanism of chip formation during grinding.

The finite element simulation models with a single abrasive were established by scholars to observe more intuitively the changes in the chip formation mechanism and its formation mechanism during grinding. Brinksmeier et al. [27] presented an overview of modeling and simulation. Fu et al. [28] analyzed the effects of grinding speed and cutting thickness on the grinding force and stress distribution. Dai et al. [29] determined the critical chip formation velocity of the nickel-based superalloy Inconel 718 by building single abrasive simulation model and found that the critical chip formation velocity was 150 m/s. Zhou et al. [30] determined the critical chip-forming thickness and critical tough-brittle transition thickness of SiC single abrasive grains by building a simulation model.

It should be emphasized that, despite the fact that a considerable number of research on single abrasives have been conducted in recent years, the finite element simulation models with single abrasive are mainly focused on the modeling simulation of a two-dimensional model, where the grinding depth of the model is constant and the actual path changes are not considered. In this study, a three-dimensional simulation model was founded according to the actual cutting thickness of the single abrasive during the grinding process. The transformation of the chip formation mechanism and the shape of the chips during the grinding process of nickel-based superalloy GH4169 were first investigated. In addition, the effect of single grain grinding speed on chip morphology and chip formation frequency was analyzed. Finally, the reasonableness and accuracy of the simulation results are verified through experiments.

2 Experimental research

2.1 Experimental equipment

As shown in Fig. 1, the grinding machine used in this paper is the M7120A, which processes workpieces with a maximum size of 630×200×320 mm. The table uses a hydraulic system with stepless speed regulation. Because the surface grinding machine’s spindle speed is constant, a Proton BT500 intelligent vector universal frequency converter is utilized to regulate the spindle speed to explore the impact of the grinding wheel’s linear speed on the chip formation. The grinding wheel diameter is 180 mm, the abrasive chosen is CBN abrasive, code 80/100 (average grain size 180 μm), medium hardness, the bond is resin, and the concentration is 100%.

The inspection equipment consists of the LEXT OLS4100 3D measuring laser microscope, the Micromeasure 3D profiler, and the Ultra Plus field emission scanning electron microscope (SEM), where the 3D measuring laser microscope mainly observes the surface profile and surface roughness of nickel-based superalloys, the 3D profiler for checking the three-dimensional profile of grinding surfaces, and the SEM is used to observe the metallographic organization and the shape of the grinding chips.

2.2 Experimental material

GH4169 is a precipitation-reinforced nickel-based superalloy with good fatigue, radiation, oxidation, and corrosion resistance properties and is capable of producing a variety
of complex-shaped components, which are widely used in aerospace, nuclear, and petroleum industries as well as in extrusion dies. The microstructure of the nickel-based polycrystalline superalloy GH4169 is observed by field emission scanning electron microscopy, as shown in Fig. 2, where the presence of many grains of varying sizes and the δ phase with an orthogonal ordered structure in the matrix of GH4169 can be significantly observed.

3 Simulation

3.1 Modeling of abrasive and workpiece material

Although CBN grinding wheels have high hardness, good self-sharpening, and high toughness, the shape of CBN abrasive grains varies significantly from one another, resulting in unrepresentative modeling of single abrasive. Diamond abrasive grains not only have high wear resistance but also have a simpler shape, so single abrasive finite element simulation tests are often carried out using diamond abrasive. The simulated workpiece is the nickel-based superalloy GH4169, whose material properties are shown in Table 1.

A material’s constitutive model represents the stress–strain–time relationship during the deformation of the material, and the selection of a correct and appropriate constitutive model can help improve the accuracy of the simulation. The Johnson–Cook constitutive equation takes into account the mechanical behavior of the metal under stress, strain, and temperature. It is suitable for describing the deformation behavior of nickel-based superalloys in the grinding environment. The Johnson–Cook model can be written as follows:

\[
\sigma = (A + B\varepsilon^n) \left(1 + n\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \left(1 - \left(\frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}}\right)^m\right)
\]  

(1)
This equation consists of three parts: The first section depicts the strain effect on flow stress. The influence of strain rate on flow stress is illustrated in the second portion. And the third part represents the effect of temperature on flow stress, where $A$ means the initial yield stress; $B$ represents the strain hardening constant; $C$ indicates the strain rate strengthening factor; $m$ denotes the thermal softening factor and $n$ is the hardening index; $\dot{\varepsilon}$ is the equivalent plastic strain rate; $\varepsilon$ indicates the equivalent plastic strain; $T$ denotes the workpiece deformation temperature; $T_{\text{melt}}$ represents the material melting temperature; and $T_{\text{room}}$ is the room temperature, where the specific values are shown in Table 2.

The chip separation criterion is used in finite element calculations to determine whether or not the chips are separated from the material matrix at the front of the abrasive grain. An accurate separation criterion can truly reflect the material’s physical properties and help to obtain reasonable results. Taking into account the stress and strain during the actual grinding process and the influence of temperature on the material, the Johnson–Cook damage model was chosen for the simulation, with fracture occurring when $D$ exceeds 1, where the Johnson–Cook damage model can be expressed as:

$$
D = \sum \left( \frac{\Delta \varepsilon^{pl}}{\varepsilon_f^*} \right)^n
$$

where $\Delta \varepsilon^{pl}$ denotes the equivalent plastic strain increment and $\varepsilon_f^*$ is the failure strain.

Failure strain $\varepsilon_f^{pl}$ can be expressed as:

$$
\varepsilon_f^{pl} = \left( D_1 + D_2 \exp(D_3 \sigma^*) \right) \left( 1 + D_4 \ln \varepsilon_0^* \right) \left( 1 + D_5 T^* \right)
$$

where $D_1$, $D_2$, $D_3$, $D_4$, and $D_5$ are damage parameters with the specific values shown in Table 3. $\sigma^*$ is the dimensionless partial compressive stress rate, in which $\sigma^* = \frac{\varepsilon^*}{T_{\text{ref}}} \dot{\varepsilon}$ (p is the compressive stress and $\gamma$ is Mises stress); $\varepsilon_0^* = \frac{\varepsilon_0^{pl}}{T_{\text{ref}}} \varepsilon_0^{pl}$ is the failure strain rate and $T_{\text{ref}}$ is the reference failure strain rate; and $T^*$ is the dimensionless temperature, in which $T^* = \frac{T - T_0}{T_{\text{melt}} - T_0}$.

The friction model uses the modified Coulomb’s law of friction:

$$
\begin{align*}
\tau_f &= \mu \sigma_n, (\mu \sigma_n < \tau_s) \\
\tau_f &= \tau_s, (\mu \sigma_n < \tau_s)
\end{align*}
$$

where $\tau_f$ is the frictional force on the blade surface in front of the abrasive grain; $\mu$ represents the friction coefficient; $\sigma_n$ denotes the positive stress; and $\tau_s$ is the shear stress.

### 3.2 Three-dimensional finite element simulation model

#### 3.2.1 Finite element models of the workpiece

As shown in Fig. 3, the grinding thickness during single grain grinding varies with time. The grinding process first gradually increases from 0 μm to the maximum undeformed cutting thickness $a_{g_{\text{max}}}$ and then rapidly decreases to 0 μm. The entire cutting area is curved in a wedge shape, and this model is difficult to build and is computationally intensive. Therefore, the workpiece model is simplified to a triangular structure to simplify the finite element model and increase the computational speed of the model. In particular, the simulation uses a 3D finite element model. This is because compared to the two-dimensional model, the three-dimensional model is a more realistic representation of the abrasive grain model and also provides a more intuitive view of the surface morphology of the single abrasive grain and the abrasive chip morphology. Therefore, the 3D finite element model is more intuitive and accurate.

The $a_{g_{\text{max}}}$ could be calculated by:

$$
a_{g_{\text{max}}} = 2 \lambda_s \left( \frac{v_w}{v_s} \right) \sqrt{\frac{d_p}{d_{eq}}}
$$

where, $a_{g_{\text{max}}}$ denotes the maximum undeformed cutting thickness; $\lambda_s$ is the circumference of the grinding wheel; $v_w$ represents the workpiece feed rate; $v_s$ denotes the grinding wheel linear speed; $d_p$ is the grinding depth; and $d_{eq}$ indicates the grinding wheel diameter.
3.2.2 Finite element models of abrasive

Diamond abrasive grains not only have high wear resistance but also have a simple shape. So, the diamond abrasive was used in the simulation. The shape of the diamond abrasive and the simulation model are shown in Fig. 4. A cutting surface of the diamond abrasive is chosen as the front face of the tool, with the cutting-edge width of \( a \) and the cutting angle of 60°. The whole model is simplified to an octahedron with an isosceles trapezoid in the main view and a rectangle in the left view.

3.3 Finite element simulation parameter setting for single abrasive

Figure 5 shows a simulation model of single abrasive grinding with a workpiece size of 60 \( \mu \)m, a width of 16 \( \mu \)m, and an \( a_{\text{gmax}} \) of 1.5 \( \mu \)m. As diamond is much harder than nickel-based superalloy GH4169, deformation and wear during grinding can be neglected, which is defined as a rigid body. The number of workpiece grid cells in Fig. 5b is 2,122,720, and the number of tool cells is 126,968.

The specific grinding parameters for the finite element simulation model are shown in Table 4.

4 Results and analysis

4.1 Surface profile analysis for grinding

Under the conditions of grinding speed \( v_s = 35 \) m/s, grinding thickness \( a_p = 40 \) \( \mu \)m, and feed rate \( v_w = 0.2954 \) m/min, the grinding surface profile of nickel-based polycrystalline superalloy GH4169 and the simulated surface profile of a single abrasive are obtained as shown in Fig. 6.

Figure 6a shows the surface morphology of nickel-based superalloy GH4169 in single abrasive simulation, and Fig. 6c shows a rear view of its XY surface, in which it can be clearly observed that the workpiece material undergoes plastic flow under the action of the abrasive, forming bulge on the front tool face and sides of the abrasive grain.

The surface morphology of the nickel-based polycrystalline superalloy GH4169 was observed under the same parameters. The surface morphology also showed bulges and microgrooves (as shown in Fig. 4b, d). The reason for this is the deformation of the material under the action of the abrasive grains. When the force exceeds the elastic limit of the material, the material undergoes plastic flow, and part of the material builds up under the action of the front face of the cutting edge and eventually forms a chip, while the other part of the material undergoes plastic flow to both sides to form a bulge or flying edge, which should be suppressed during the grinding process.

4.2 The chip morphology

To visualize the change in chip morphology during the grinding process, the grinding abrasive is concealed, and the chip morphology of single abrasive grinding a nickel-based polycrystalline superalloy GH4169 is obtained, as shown in Fig. 7a. And to verify the accuracy of the chip morphology during the simulation, a chip collecting box is installed on the grinding machine table to collect the chips generated.
during the grinding test, and the surface morphology is studied using the Ultra Plus field emission scanning electron microscope to get Fig. 7b.

As shown in Fig. 7a, nickel-based polycrystalline superalloy GH4169 mainly produces serrated chips during grinding, which have two distinct surfaces: the contact surface and the free surface. The side that is biased towards the front face of the abrasive grain is called the contact surface, which is mainly smooth and flat and has traces of abrasive grains sliding over the inner surface of the abrasive chip. Its outflow direction is basically the same as the angle of the abrasive grain, while the bulge on the side of the abrasive grain also forms burrs and flying edges. The other side is called the free surface. Compared with the contact surface, the free surface is mainly manifested as a lamellar shape. The reason for this is that when the stress on the shear surface exceeds the strength limit of the material in the process of shaping and deforming the material under the action of the abrasive, the material is sheared to form lamellar nodules. Figure 7b shows the shape of the chips collected at the same grinding parameters, in which the free surface and the contact surface of the chips can be clearly observed, and the shape is similar to the simulation results.

During the machining process, the interaction between the abrasive and the workpiece generates a large amount of grinding heat. At the same time, the abrasive grain generally has a negative front angle. Thus, the grinding will intensify the material deformation and generate high temperatures. As a large amount of grinding heat is not released in time, it makes the material more susceptible to adiabatic shearing and the formation of jagged abrasive chips, the formation principle diagram of which is shown in Fig. 8a.

Nickel-based superalloys have high strength, thermal strength, and low thermal conductivity and are typically difficult-to-machine materials, so the grinding temperature generated during the grinding process is difficult to conduct out and the degree of adiabatic shear is more pronounced, making it easy for the shear slip to occur. Figure 8b shows the single abrasive simulation of nickel-based superalloy GH4169. In this picture, the jagged lamellar abrasive chips are visible, and there are clear bulges in the shear surface of the chip.

Table 4  Grinding parameters applied in the finite element simulation model

| Grinding speed/(m/s) | Feed rate/(m/min) | Grinding depth/(µm) | Maximum undeformed cutting thickness/(µm) |
|---------------------|-------------------|---------------------|------------------------------------------|
| 20                  | 0.1688            | 40                  | 1.5                                      |
| 25                  | 0.2110            |                     |                                          |
| 30                  | 0.2532            |                     |                                          |
| 35                  | 0.2954            |                     |                                          |
| 45                  | 0.3798            |                     |                                          |
| 60                  | 0.5064            |                     |                                          |
To explore the process of serrated abrasive chip formation, six images (Fig. 9a, b) were selected which correspond to the formation of chip in the previous section, material bulge, material fracture, material shear slip, material being squeezed to form a bulge, and the formation of the new chip. As shown in Fig. 9, the swarf gradually thickens during the grinding process, and when the swarf thickness reaches a certain value, it cracks and quickly thins out. The formation of chips repeats the process periodically. This is because during the grinding process, the shear angle of the cutting edge decreases and the thickness of the grinding chip increases, resulting in more tremendous stress on the chip, when this stress reaches the fracture limit of the material, the material fractures, at which point the back engagement decreases and the shear angle increases. In addition, it can be observed that a bulge is generated near the center of the shear surface of the abrasive chip. This is because, in the process of chip formation, the material does not only undergo shear slip, and the center of the shear surface of the abrasive chip is also squeezed to form a bulge.

4.2.1 Influence of variation in cut thickness of single abrasive on chip morphology

At the maximum undeformed chip thickness of 1.5 µm and the single abrasive grinding speed of 35 m/s, the change in chip morphology with cutting thickness is shown in Fig. 10.

When the cutting thickness of single abrasive is 0.06 µm, the workpiece material forms a slight bulge at the front of the abrasive, and no chips are formed at this time. Then, at the cutting thickness of 0.15 µm, the material deforms plastically and builds up in front of the abrasive grain, increasing the bulge and producing a small number of abrasive chips. By 0.45 µm, the abrasive chips begin to increase but are mostly crumbly and unstable. At 0.75 µm, the chip formation frequency rises and begins to stabilize, but the sawtooth shape of the chips is not significant. However, the sawtooth shape chips can be clearly observed from 1.05 to 1.35 µm and are more serrated at 1.35 µm compared to those at 1.05 µm. Therefore, the workpiece material undergoes four successive stages of grinding: rubbing–ploughing–unstable chip formation.
formation–stable chip formation. The material is deformed elastically by the force when the abrasive grain starts to come into contact with the workpiece. Subsequently, the chip thickness of a single abrasive grain increases. When the force of the abrasive grain on the workpiece is greater than the elastic limit of the material, the workpiece material will be plastically deformed, thus causing the plastic flow of material to both sides of the cutting edge or the front tool face to form a bulge.

To further explore the variation of the workpiece material and abrasive interaction mechanism in the three stages of rubbing–ploughing–cutting, the stress diagrams of the three stages are retrieved from the simulation results, as shown in Fig. 11. When the thickness of single abrasive is less than 0.06 μm, the interaction between the abrasive and the workpiece is small, with the maximum von Mises stress of only 2.216 GPa. At the same time, the workpiece material only undergoes elastic deformation, resulting in the abrasive cutting through the workpiece and not producing chips, as shown in Fig. 11a. When the cutting depth is about 0.06 to 0.18 μm, the force between the abrasive grain and the workpiece will exceed the material’s elastic limit, with the maximum von Mises stress of 2.328 GPa. At the same time, the surface of the workpiece is plastically deformed, resulting in plastic flow and the formation of a bulge, as shown in Fig. 11b. When the grinding depth continues to increase beyond 0.18 μm, at which point the maximum von Mises stress reaches 2.791 GPa, the material will tear down from the surface of the base material and begin to form chips, as shown in Fig. 11c.

During the grinding process, the grinding force oscillates at a high frequency in a violent cyclic manner, and each fluctuating cycle of the grinding force corresponds to the formation of a chip. The grinding force increases rapidly at the beginning of chip formation, decreases sharply after chip formation, and then increases when new chips are generated,
a process that repeats itself. And the correctness of this theory has also been verified by the researchers involved [28, 29, 31]. To further explore the effect of the variation of the cutting thickness of the single abrasive on the chip formation stage, the values of the grinding force variation throughout the grinding process are retrieved, as shown in Fig. 12.

In Fig. 12, ①, ②, and ③ correspond to the three stages of the grinding process: rubbing, ploughing, and chip formation. As the grinding distance increases and the depth of cut changes, the peak grinding forces show a gradual increase followed by a sharp decrease. The peak grinding force gradually increases from 0 to 1.8 N when the cutting thickness of a single abrasive gradually increases to the maximum cutting thickness $a_{\text{max}}$. Subsequently, the peak grinding force also drops sharply to 0 N due to the sharp reduction in the cutting thickness of the single abrasive. Specifically, when grinding is in the rubbing stage, the constant squeezing of the abrasive results in a linear increase in grinding force to 0.28 N. When grinding is in the ploughing stage, a slight bulge is produced on the front face of the grinding abrasive. However, there is no cyclicity in the change of grinding forces. When grinding is in the chip formation stage, it can be clearly observed that during the pre-chip formation, the chip segmentation frequency is unstable, and the grinding forces are not cyclical. While after point $e$, it enters a stable chip formation state, and the grinding force shows a cyclical increase.
Since the chip is in a stable chip state after point $e$, to quantitatively analyze the change in chip formation frequency during grinding, a total of 7 points from $e$-1 are intercepted as data for calculating the chip formation frequency, where the chip segmentation frequency is the reciprocal of time. Figure 13a shows the change in chip segmentation frequency during single abrasive grinding.

As shown in Fig. 13a, the chip segmentation frequency of GH4169 gradually decreases with the increase of the cutting thickness of the single grinding abrasive. In particular, the chip segmentation frequency decreases sharply from 24 to 20 kHz at grinding distances between 10 and 24 µm; at grinding distances between 24 and 36 µm, the chip segmentation frequency changes more slowly; at grinding distances between 36 and 46 µm, the chip segmentation frequency decreases sharply from 16 to 11 kHz. Figure 13b shows the chip morphology observed by SEM in the grinding test. When chip formation begins, the chip shear slip surface is narrower, and jagged units are formed more frequently because of the low chip depth. However, as the thickness of the cut increases, the width of the shear slip surface of the chip increases, and the frequency of formation of serrated units on its free surface decreases. The results are the same as for the single grain simulation.
4.2.2 Influence of grinding speed on chip morphology

To explore the variation of chip morphology at different speeds, the chip morphology was observed at grinding speeds $v_r = 20$ m/s, 25 m/s, 30 m/s, 35 m/s, 40 m/s, and 60 m/s, respectively. The maximum cutting thickness of the single abrasive is 1.5 µm, and the grinding distance is 51 µm. The finite element simulation results are shown in Fig. 14A. Figure 14B shows the grinding chips collected under the same experimental parameters, and the grinding chip morphology was observed by scanning electron microscopy.

As shown in Fig. 14A, the chip morphology in this grinding speed range is mainly in the form of serrated flakes, the free surface is serrated, and the contact surface is smooth due to the extrusion of the abrasive. Generally speaking, as the grinding speed increases, the chip shape changes from a unitary laminated serrated chip to a continuous serrated chip, which then develops into a continuous ribbon chip. When the grinding speed is between 20 and 30 m/s, the chip pattern is unitary lamellar serrated. At 35 to 40 m/s, the chip pattern is continuous and serrated. At 35 to 40 m/s, the chip pattern is continuous and serrated. At a grinding speed of 60 m/s, the chip pattern is a continuous strip, but the free surface of the chip still has a fine flaky layer. The reason for this is that GH4169 has a significant strain rate effect in this grinding speed range. When the grinding speed is small, the material strain hardening effect has a more significant influence on the material stresses, resulting in higher flow stresses and material hardness in the first deformation region than in other areas. Thus, under the action of the abrasive grain, the material in the first deformation zone forms a bump on the unmachined surface in the direction of shear, followed by a lamellar, serrated abrasive chip along the front face of the abrasive grain. As the grinding speed increases, the material hardening effect on the material stress gradually decreases, its shaping index decreases, and it is easier to form continuous or banded chips.

As shown in Fig. 14B, the chip morphology is mainly serrated at different grinding speeds, and the free surface and contact surface morphology are consistent with the morphology obtained from the simulation. In addition, it can be observed that when the grinding wheel line speed is 20 m/s and 25 m/s, the shear slip surface of the chip is wider, and the frequency of segmentation of serrated units on its free surface and the degree of serration are lower. However, as the wheel line speed increases and when the wheel line speed is 30 to 60 m/s, the shear slip surface becomes narrower, and the frequency of segmentation of
serrated units on its free surface and the degree of serration increase. The reason for this is that as the grinding speed increases, the rate of material deformation increases, material plasticity decreases, and toughness increases, making it easier to form abrasive chips and shear slip occurs more frequently. What is more, compared to the FEM simulation results, the surface profile of the experimentally collected grinding chips is more regular. This is due to the fact that the experiments were carried out in a coolant environment, which has a certain cooling and lubricating effect. The water-absorbing oil film attached to the interface between the abrasive grain and the surface being machined uses its ductility to play a better role in reducing wear and lubrication during the grinding process, resulting in a more regular surface profile.

The above method of calculating the chip formation frequency for the stable chip formation phase gives the stable chip formation frequency at different speeds, as shown in Fig. 15. It can be observed from Fig. 15 that the chip segmentation frequency of GH4169 decreases with the increase of grinding distance in the range of simulation parameters and increases from 14 to 40 kHz with the addition of grinding speed (25 ~ 60 m/s) when the grinding distance is the same. The trend of the chip segmentation frequency was consistent with the test results, which confirmed the reliability of the model establishment. This is due to the fact that GH4169 is in the zone of significant strain rate effect under the simulation parameters, as the grinding speed increases, the material plasticity decreases, and toughness increases more easily to form grinding chips, so the greater the grinding speed, the higher its chip segmentation frequency.

5 Conclusions

In this paper, the mechanism of chip formation in the grinding process of nickel-based superalloy GH4169 was investigated. By establishing a three-dimensional finite element model of grinding based on the actual variation of the cutting thickness of a single abrasive grain, the variation of chip morphology during grinding process and the effect of grinding speed on chip morphology were analyzed. At the same time, the simulation results were also verified by collecting grinding chips with the same grinding parameters. The following results were obtained in this study.

1. The nickel-based polycrystalline superalloy GH4169 mainly generates serrated chips during the grinding process, which has two typical surfaces: the contact surface and the free surface. The grinding force varies cyclically and its fluctuations correspond to the chip formation process.

2. The grinding process can be divided into four stages according to the change in the mechanism of action between the abrasive and the material: rubbing, ploughing, unstable chip formation, and stable chip formation. The frequency of chip segmentation decreases as the grinding distance increases, mainly attributed to the increase in the cutting thickness of the single abrasive grain. In addition, the grinding speed is also a significant factor affecting the frequency of chip formation in grinding. Specifically, the higher the grinding speed, the higher the frequency of chip segmentation in grinding.

3. As the grinding speed increases, the chip morphology changes from a lamellar chip to a continuous chip pattern and then develops into a continuous band of chips. At a grinding speed of 20 to 30 m/s, the chip pattern becomes a unitary lamellar chip; at a grinding speed of 35 to 40 m/s, the chip pattern becomes a continuous serrated chip; at a grinding speed of 60 m/s, the chip pattern becomes a continuous ribbon chip, but the free surface of the chip still has a fine lamellar layer.

Author contribution Tao Zhu: Writing—original draft, software, investigation, visualization. Ming Cai: Writing—original draft, review and editing, conceptualization, funding, visualization. Yadong Gong: Conceptualization, methodology, formal analysis. Xingjun Gao: Supervision, investigation, methodology. Ning Yu: Data curation, formal analysis. Xiang Li: Data curation, formal analysis.

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Declarations

Competing interests The authors declare no competing interests.

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