Modeling and simulation of a single abrasive grain micro-grinding force and temperature of bone

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Abstract
Grinding methods have been widely used in orthopedic surgery, which has high requirements for surface quality, grinding force and temperature control. It is necessary to explore the influence of micro-grinding parameters on the grinding force temperature from a microscopic perspective. This paper describes the micro structure, composition and thermodynamic properties of bone. From the perspective of the single abrasive grain, the single abrasive grain cutting model is established, and the single abrasive grain cutting force equation is derived. ABAQUS is used to establish a 2D cutting simulation model of abrasive grains, and the internal structure of the bone material is considered, and the bone micro structure model (including osteon orientation, matrix, cement line) is established. The simulation study is carried out on the cutting direction of the abrasive grains in parallel, vertical and cross with the axial unit axis. The study of the relationship between force and temperature and cutting parameters shows that the abrasive cutting force increases with the increase of grinding speed and grinding depth. The cutting force is the largest in the vertical cutting mode, the cutting force is the second in the cross cutting mode, and the cutting force is the smallest in the parallel cutting mode. Finally, the comparison between theory and simulation shows that the theoretical analysis results are consistent with the finite element simulation results, which verifies the correctness of the theoretical model of single abrasive grain cutting force.

Keywords: Bone, Micro-grinding, Single abrasive grain, Cutting model, Simulation model

1. Introduction
Orthopedic surgery has high requirements for surface quality, grinding force and temperature control. Reasonable selection of grinding parameters and tool parameters has a direct impact on surgical quality and postoperative recovery. The grinding heat and vibration generated during bone grinding have a certain influence on the bone and its surrounding tissues, and the effect of grinding heat is most significant. Because of the low conductivity of the bone, only a small part of the heat generated is transmitted to the inside of the bone, and most of the heat accumulates on the grinding surface, causing the surface temperature to rise rapidly. The bone is biologically active, so if the temperature is too high, the activity of the enzyme will decrease, resulting in a decrease in the activity of the bone and surrounding soft tissues. Previous studies have found that once the temperature is higher than 50°C, it will lead to the death of bone and its surrounding soft tissue cells (Karaca et al., 2011). Therefore, it is necessary to study the bone grinding temperature, explore the influence of grinding parameters on the grinding temperature, to properly control the grinding parameters, and improve the grinding efficiency while ensuring low temperature.

Simulation techniques are used to study bone grinding to balance research costs and efficiency. At present, macroscopic bone cutting research based on homogeneous model is widely studied, but less research is conducted on micro-cutting bone structure characteristics. M. Mitsuishi et al. (Mitsuishi et al., 2004a,2005b) studied the change of cutting force during bone micro-cutting from the perspectives of bone density, tool rake angle and cutting depth. K. Alam et al. (Karaca et al., 2011) studied the cortical bone plane cutting problem and used the finite element analysis method to describe the relationship between cutting force and cutting parameters. Shih et al.(Shih et al., 2012) studied the grinding process of the skull, used the experimental method to predict the grinding temperature, and established the
skull thermal model, using the finite element method to visualize the thermal damage of the skull. Tai et al. (Tai et al., 2013) predicted the neurosurgical bone grinding temperature based on the thermal energy conversion equation and the finite element heat transfer model for the linear correlation between the bone grinding heat and the motor input electrical energy. Wang G et al. (Wang et al., 2016) established a heat transfer model and a finite element model, and used the inverse heat transfer method to predict the temperature of skull base neurosurgical bone grinding through modeling and simulation. Yang M et al. (Yang et al., 2017) established a microscopic skull grinding model to simulate the temperature field of skull grinding under different cooling conditions. Yuan-Kun Tu et al. (Yuan-Kun et al., 2008; Tu et al., 2010) established a dynamic elastic-plastic finite element model to simulate the temperature rise during bone drilling. S. Sezek et al. (Sezek et al., 2012) used a finite element simulation method to analyze the temperature changes under different drilling parameters (such as rotational speed, feed rate, drill diameter, bone density, and axial force) during bone drilling. Zhang Lihui et al. (Zhang et al., 2013) established a temperature thermal model for skull base neurosurgery grinding which used the inverse heat transfer method (IHTM) to investigate the bone grinding temperature and used finite element analysis method to study the bone temperature rise caused by grinding.

This paper first introduces the material properties of bones, including the micro structure and thermodynamic properties of bone. From the perspective of the single abrasive grain, the single abrasive grain cutting model is established, and the single abrasive grain cutting force equation is derived. Then, the single abrasive grain cutting process

### 2. Material properties of bone

Bone is a complex biological tissue material with anisotropy. There are certain requirements on the grinding temperature and the grinding force. If the temperature and force exceed a certain value, it will cause damage to the bone and surrounding tissues (Eriksson et al., 1984). From the microscopic point of view, the composition and internal structure of bone are closely related to the thermodynamic properties of bone. The forces and temperatures in different cutting directions may be different.

#### 2.1 Bone micro structure and composition

As shown in Fig.1(a) (Natalie et al., 2014; Yaogeng C et al., 2018), the cortical bone layer is composed of osteon orientation and bone matrix, and the osteon orientation is a fundamental building unit of the cortical bone at the microscopic scale which are filled with a hard matrix, and has a length of 3-5 mm and a diameter of 50-250 μm. There is a relatively thin layer of cement line between a single osteon orientation and the matrix, between 1-5 μm thick, which separates the osteon orientation from the matrix. The osteon orientation and the matrix are "glued", the strength of the cement line is smaller than the osteon orientation and the matrix, so when the bone breaks, the crack generally expands along the cement line. As shown in Fig.1(b) (Natalie et al., 2014; Yaogeng et al., 2018), the Harvard canal (also known as the second osteon orientation), which exists inside the osteon orientation, is mainly responsible for transporting blood. Therefore, the structure of the cortical bone makes the bone anisotropic, that is, exhibits different thermodynamic properties in different directions. Studies have shown that the stiffness and strength of the osteon orientation in the longitudinal direction is higher than the matrix and the cement line, and the matrix portion is isotropic. It can be found from the cross-section perpendicular to the axis of the osteon orientation that the osteon orientations are randomly distributed, but when the numerical simulation model is established, it is generally assumed that it is distributed according to a certain regularity, such as a regular hexagonal distribution or a regular quadrilateral distribution. The ABAQUS was used to simulate the two types of arrangement, and compared with the cutting experiment, it was found that the regular quadrilateral arrangement is closer to the experimental results (Yin J., 2016).
2.2 Bone thermodynamic properties

As a heterogeneous, elastoplastic biomaterial, the stress and strain relationship of bone materials is divided into elastic strain phase and plastic strain phase shown in Fig.2. OA is the elastic strain phase, the yield limit is at point A, and the OA is approximately straight, that is, the stress-strain of the bone should be proportional to the Hooke's law. AB is the plastic strain phase, the strength limit is at point B which is also called the break point. As the cutting progresses, the elastic strain first occurs, the stress and strain increase continuously to reach the yield limit, and then plastic strain occurs until the strength limit is reached.

Bone is biologically active. When the temperature is above a certain value, the bone will be damaged, and the time required for bone to be exposed to necrosis at different temperatures will be different. The temperature-time curve of osteonecrosis obtained from the Abouzgia’s work (Abouzgia et al., 1997) is shown in Fig.3. It can be seen from the figure that when the temperature reaches 70°C or above, the bone will be thermally necrotic in an instant, and the higher the temperature, the shorter the time required for osteonecrosis. When the temperature is above 55°C, osteonecrosis occurs in a short period of time. When the temperature is lower than 55°C, the time required for osteonecrosis becomes longer as the temperature decreases. Davidson et al. (Davidson et al., 2000), used bovine femur as the research object. The measured thermal conductivity of the cortical bone of bovine femur in the circumferential direction, the long axis direction, and the radial direction were 0.53±0.030 W/(m·K), 0.58±0.018 W/(m·K), and 0.54±0.020 W/(m·K) respectively, the difference is small, so it can be approximated that the thermal conductivity of the femur is isotropic. This provides theoretical support for the assumption that the bone is assumed to be an isotropic homogeneous material during simulation.
Studies have shown that human bone properties are closest to the bovine femur. The cortical bone structure of cattle is relatively uniform, the growth direction is easy to distinguish, the anisotropy is obvious, and both primary and secondary bones exist, similar to human bone. Table 1 shows the thermodynamic constants of bovine femurs obtained by experiments and other methods from 1970 to 2018 by Davidson et al. (Davidson et al., 2000).

Table 1 Thermodynamic properties of bovine cortical bone

| Serial number | Symbol | Thermodynamic properties                      | Value   |
|---------------|--------|-----------------------------------------------|---------|
| 1             | $K$    | Thermal conductivity $W/(m \cdot K)$           | 0.452   |
| 2             | $c$    | Specific heat $J/(kg \cdot K)$                | 1640    |
| 3             | $\mu$  | Coefficient of friction                        | 0.35    |
| 4             | $h$    | Radiation coefficient                          | 1       |
| 5             | $\rho$ | Dense bone density $kg/m^3$                    | 1700    |
| 6             | $\varepsilon_0$ | Failure strain %                             | 5       |
| 7             | $E_0$  | Osteon orientation elastic modulus $GPa$      | 20.8    |
| 8             | $E_m$  | Matrix elastic modulus $GPa$                  | 26.3    |
| 9             | $E_e$  | Average elastic modulus $GPa$                 | 20      |
| 10            | $G$    | Shear modulus $GPa$                            | 3.3     |
| 11            | $X_r$  | Longitudinal tensile limit $MPa$              | 135     |
| 12            | $X_c$  | Lateral tensile limit $MPa$                   | 202     |
| 13            | $S$    | Shear limit $MPa$                              | 65      |
| 14            | $b$    | Poisson's ratio                                | 0.3     |
| 15            | $aL$   | Linear expansion coefficient $mm/\degree C$   | $2.75 \times 10^{-5}$ |
3.Single abrasive grain cutting theory

The surface of the grinding tool consists of a large number of irregular, different shapes of abrasive grains. It is difficult to study directly from the macroscopic aspect when studying the grinding mechanism. Therefore, the slip test is often carried out from the perspective of a single abrasive grain to study the grinding mechanism. Brecker et al. used a single abrasive grain of a pendulum-cutting motion to perform a cutting experiment to study the ploughing effect of abrasive grains (Brecker et al., 1974). Brinksmeier et al. performed a single abrasive grain scratch experiment to study the mechanism of the generation of hardened steel grinding chips during grinding (Brinksmeier et al., 2003). Matsuo et al. studied the effects of abrasive morphology on cutting force and chip formation by using single-grain micro-cutting experiments on steel and alumina with different grain sizes of diamond and CBN abrasive grains (Matsuo et al., 1989). Ohbuchi et al. performed orthogonal cutting experiments on S50C steel using diamond abrasive grains with different negative rake angles analyze to the effects of cutting speed and negative rake angle on chip formation, cutting temperature and cutting force (Ohbuchi et al., 1991). Anderson et al. Performed cutting experiments by a diamond abrasive grinding tool with a radius of 0.508 mm to analyzed the effect of cutting speed on cutting force, material removal mechanism, and material bulging (Barge et al., 2008). At present, when domestic and foreign scholars are studying single abrasive grain cutting, most of them use finite element and molecular dynamics methods to simulate the cutting deformation process of materials. In the single abrasive grain cutting simulation, the shape of the abrasive grain is mostly simulated by using a geometry such as a sphere, a cone, a truncated cone, or a polygonal pyramid.

There are a large number of irregularly distributed abrasive grains on the surface of the spherical grinding tool. The grinding process is the result of the comprehensive action of a large number of irregularly distributed abrasive grains. It is difficult to directly study from a macroscopic point of view. Therefore, it is considered to conduct corresponding theoretical research from the perspective of a single abrasive grain. The single abrasive grain cutting is a common simplified mode and an important method for studying grinding related problems. The bone grinding process is shown in Fig. 4. A spherical grinding tool is used to grind a groove on the bone. The grinding depth is $a$, the feed speed is $v$, the rotational speed is $\omega$, and the diameter of the spherical grinding tool grinding head is 4mm. In the micro-grinding process, the grinding depth is small compared to the contact arc length, and its size is negligible. The contact arc length is directly represented by a straight line $l$. The partial spherical grinding tool surfaces involved in grinding is shown in Fig.5, and a single abrasive grain is selected on the spherical surface for analysis. The abrasive grains with complex shapes are generally simplified into a spherical shape, a cone shape or a truncated cone shape. Since the shape of the truncated cone is reasonable, this paper will study the abrasive grains based on the the truncated cone shape.

![Fig. 4 Physical model of grinding with spherical grinding tool](image)

![Fig. 5 Partial spherical grinding tool surfaces involved in grinding](image)

During the grinding process, the cutting thickness of a single abrasive grain involved in cutting is constantly changing. There is a critical cutting thickness, that is, the maximum undeformed cutting thickness. This critical cutting thickness is essentially the maximum cutting depth of the cutting edge of a single abrasive marked as $h_n$. The maximum undeformed cutting thickness $h_n$ has a significant effect on micro machining, especially when the thickness is close to the micro cutting edge radius, and is an important grinding factor to characterize the grinding process. It not only affects the grinding force, but also affects the grinding temperature. If the cutting thickness is less than $h_n$, the workpiece will only deform without chip formation. Figure 6 shows the cutting path and cutting thickness of a single
abrasive grain, $r$ is the radius of the grinding tool, $\omega$ is the rotation speed of the grinding tool, $v$ is the grinding feed speed, $v_w$ is the grinding tool line speed, i.e. the abrasive grain line speed, $d$ is the diameter of the grinding tool, $a_p$ is the grinding depth, the angle $\alpha$ is the angle of the coordinate system $[O]$ at which the abrasive grain turns around the point $O$, and the angle $\xi$ is the complementary angle of the angle $\alpha$. $S$ is the moving distance of the abrasive grains along the feed direction before the next adjacent abrasive grain is cut, and $l_s$ is the distance between the adjacent abrasive grains. The abrasive grains fixed in the abrasive tool rotate as the grinding tool about a fixed axis, and the bone workpiece performs a linear feed motion at a speed $v_w$ at the same time, so that the single abrasive grains perform a composite motion relative to a point in the bone workpiece. As can be seen from the Fig.6, the maximum undeformed cutting thickness $h_m$ is approximately equal to the length of $AC$, the length of $OC$ is $l_s$, and the length of $OA$ is $l_s$.

Fig. 6: Schematic diagram of geometric relationship in single abrasive grain cutting

$s$ is length along feed direction and represented as $tv$. Where $t$ is the requested time which value is $l_s$ (distance between adjacent grains along circumferential direction) divided by $v_w$ (circumferential velocity). Then, the distance $s$ of single abrasive grain moving distance $l_s$ between the adjacent abrasive grains according to speed $v$ in feed direction is:

$$s = tv = \frac{l_s v}{v_w}$$

(1)

$$v_w = \omega r' = \omega r \cos \xi$$

(2)

From the geometric relationship: The length of $OA$ can be expressed by the following equations:

$$h_m = l_i - l_s = r - l_s$$

(3)

$$l_s = (r \cos \xi - S)^2 + (r \cos \alpha)^2 = (r^2 + s^2 - 2sr \cos \xi)^{\frac{1}{2}}$$

(4)

As can be seen from Fig. 6:

$$\sin \xi = 1 - \frac{a_p}{r}$$

(5)

From the above equations:
Considering the size effect and other factors in the micro grinding process, the modified coefficient $M_d$ is introduced to characterize the influence of other parameters on the maximum undeformed cutting thickness, and the expression of the maximum undeformed cutting thickness $h_m$ is obtained:

$$h_m = M_d \left[ r - \left( r^2 + s^2 - 2s \sqrt{a_s (2r - a_p)} \right)^{\frac{1}{2}} \right]$$

The grinding force is an important indicator of the quality of grinding. If the grinding force during grinding is large, cracks may occur in the bone tissue, causing secondary damage to the bone. The grinding temperature is affected by the grinding force. When studying the temperature, we must first study the grinding force theoretically. Grinding is the composite effect of a single abrasive grain. Due to the particularity of the spherical grinding tool, it is difficult to directly study its grinding force. Therefore, from the perspective of a single abrasive grain which is reasonably simplified, a single abrasive grain cutting force model is established. From the above analysis, the single abrasive grain is simplified into a circular truncated cone, and the grinding force of the abrasive grain is perpendicular to the surface without considering the friction. Figure 7 is the single abrasive grain cutting model when the cutting thickness is greater than the minimum undeformed cutting thickness. A point is selected for analysis, at which point the cutting force can be decomposed into normal force and tangential force.

In the micro-cutting range of a single abrasive grain, the value of the force is calculated using the Merchant model, which can be used on infinitesimal elements (Liu et al., 2001; Son et al., 2005). If the depth of cut exceeds the maximum undeformed cutting thickness, the chips are formed and the force on the micro-element can be decomposed into the tangential force $dF_{cx}$ and the normal force $dF_{cz}$. The forces $F_{cx}$ and $F_{cz}$ of a single abrasive grain in Fig.7 are tangential forces and the normal during the cutting process. In Fig. 8, $r_t$ is the radius of the top of the truncated cone, $r_b$ is the radius of the bottom end of the truncated cone, $h$ is the height of the entire abrasive grain, and $r_t$ is the radius of the truncated cone. The force $dF_{cz}$ can be derived by the Merchant's force expression:

$$dF_{cz} = \frac{\tau_s \cos(\beta - \alpha)}{\sin \phi \cos(\phi + \beta - \alpha)} \cdot dt$$

Where: $\tau_s$ is the shear strength of bone, $\beta$ is the instantaneous friction angle, $\phi$ is shear angle and $\alpha$ is the instantaneous rake angle. As can be seen from the geometric relationship in the above figure,
\[ dt = r \sin \theta d\theta \]  

(9)

\[ F_{cs} \] and \( F_{cz} \) can be expressed by Eq. (10) and (11):

\[ F_{cs} = \int_{0}^{h} \frac{r_{s} \cos(\beta - \alpha)}{\sin(\pi/4 - \beta/2 + \alpha/2) \cos(\pi/4 + \beta/2 - \alpha/2)} \cdot ds_{s} \]  

(10)

\[ F_{cz} = \int_{0}^{h} \frac{r_{s} \sin(\beta - \alpha)}{\sin(\pi/4 - \beta/2 + \alpha/2) \cos(\pi/4 + \beta/2 - \alpha/2)} \cdot ds_{s} \]  

(11)

The tangent of the taper angle \( \varphi \) is as shown in Eq. (12).

\[ \tan \varphi = \frac{h_{i}}{r_{e} - r_{a}} \]  

(12)

Fig. 8 Geometric model of single abrasive grain in the shape of truncated cone

The geometric relationship can be expressed by Eq. (13).

\[ r_{i} = r_{a} - \frac{h_{i}}{\tan \varphi} = r_{a} - \frac{h_{i}(r_{a} - r_{e})}{h_{i}} \]  

(13)

Therefore, the differentiation element \( ds_{s} \) of the cross-sectional area in which a single abrasive grain participates in cutting is as shown in Eq. (14).

\[ ds_{s} = 2r_{i}dh = 2 \left[ r_{a} - \frac{h_{i}(r_{a} - r_{e})}{h_{i}} \right] dh \]  

(14)

The mathematical model of the component force \( F_{cs} \) and \( F_{cz} \) of the single abrasive grain grinding force is shown in Eq. (15) and (16), which is integrated over the height \( h_{m} \), where \( h_{m} \) is a function of the speed, feed rate, depth of grinding, and diameter of the tool. The cutting force of a single abrasive grain during cutting is as shown in Eq. (17).
4. Simulation model of cutting force and temperature of single abrasive grain

4.1 Establishment of a single abrasive grain cutting model

The shape of the abrasive grains on the spherical grinding tool is irregular, so the abrasive grains are simplified into a simple geometric model for the convenience of research. In order to simplify the calculation, considering that the abrasive grain cutting thickness is larger than the maximum undeformed cutting thickness, only the abrasive grain cutting stage is simulated and the sliding and ploughing stages are ignored. A simplified geometric model of abrasive grain and bone was established to verify the theoretical model of single abrasive grain cutting force, as shown in Fig. 9. The research object is cortical bone, and the material of the spherical grinding tool is diamond. The single abrasive grain is simplified to a truncated cone shape having a diameter of 0.2 mm on the upper circle, a diameter of 0.05 mm on the lower circle, and a height of 0.2 mm. The bone has a length of 1 mm and a width of 0.25 mm. The abrasive grain moves to the left at a speed $V$ with a cutting thickness of $h$. The temperature and force under different cutting speeds and depths are studied through ABAQUS to simulate by orthogonal cutting method, and the variation of temperature and force under different parameters is analyzed, which is compared with the results obtained by the theoretical model of single abrasive grain cutting force.

![Fig. 9 Simplified process of single abrasive grain](image)

4.2 Constitutive equation of material

In the finite element analysis, constructing the constitutive equation of the material is one of the essential key steps. At present, common models used to represent the mechanical relationship of materials are Bamman model, Maekawa model, Johnson-Cook model and Oxley model. The Johnson-Cook model can be used to describe the rational constitutive model of materials under high strain rate, high temperature and large deformation, and is widely used in cutting simulation analysis.

The flow stress expression of the Johnson-Cook model is as follows:

$$
\sigma = (A + B\varepsilon^*) (1 + C \ln \dot{\varepsilon}) \left(1 - T^m \right)
$$

(19)
Where: $\sigma$ is the total flow stress (MPa), $\varepsilon$ is the equivalent plastic strain, $\dot{\varepsilon}$ is the strain rate ($s^{-1}$), $A$ is the yield stress (MPa), $B$ is the work hardening modulus (MPa), $C$ is the strain rate sensitivity coefficient, $m$ is the temperature sensitivity coefficient, $n$ is the hardening coefficient, $T^*$ is the relatively stable temperature (°C). The first term on the right side of the equation represents the strengthening effect of the material under large deformation. The second term represents the strain rate sensitive effect of the material, i.e., the relationship between the plastic flow stress and the logarithm of the strain rate. The third term represents the heat sensitive effect of the material, i.e., the relationship between stress and temperature. The Johnson-Cook model parameters of the bone (Remache et al., 2019) are shown in Table 2.

| A (MPa) | B (MPa) | n  | C   | m   | $T^*$ (°C) |
|---------|---------|----|-----|-----|------------|
| 50      | 101     | 0.08 | 0.03 | 1.03 | 875        |

4.3 Contact friction type and meshing
Various contact forms such as self-contact, face-to-face contact, and universal contact can be set in ABAQUS. The established simulation model contact type is a face-to-face contact, the surface of the abrasive grain is defined as a first surface, and the surface of the bone is defined as a second surface, and the first surface can pass through the second surface. The cutting process is simulated by ABAQUS, which involves the feed movement of the abrasive grains. The motion contact method can be selected in the mechanical constraints, and the default values can be selected in the weight coefficient and the contact control. The initial temperatures assigned to bones and tools are 37°C and 20°C, respectively. In the meshing, the grid size should be reasonably controlled, and the mesh density should be controlled by the seed in ABAQUS. The higher the density, the higher the accuracy of the result. When the element size tends to be infinitely small, the calculated value is approximately equal to the true value. The unit type is quadrilateral(CPE4RT) in this paper, and the algorithm option is to minimize the mesh transition.

5. Results
5.1 Simulation results of cutting force and temperature varying with cutting parameters
The factors affecting the grinding temperature and the grinding force are multifaceted, so the secondary influence factors are ignored. The method of controlling single variables is mainly used to study the effects of single abrasive grain cutting speed and cutting thickness on temperature and force and the variation and distribution of force and temperature during cutting. The simulation process when the abrasive grain moving speed is 5 mm/s and the cutting thickness is 10μm is shown in Fig.10. Figure10(a) is a temperature field distribution diagram when the abrasive grain and bone come into contact, Figure10(b) is a temperature field distribution diagram when the abrasive grains start to cut the bone, Figure10(c) is a temperature field distribution diagram when chip formation begins, Figure10(d) is a temperature field distribution diagram during stable cutting. The stress distribution during single abrasive grain cutting is shown in Fig.11.

Simulation of a single abrasive grain under different parameters was performed by ABAQUS. The cutting thicknesses are 10μm, 20μm, 30μm, 40μm, 50μm, 60μm, and the feed rates are 1 mm/s, 2 mm/s, 3 mm/s, 4 mm/s, 5 mm/s, 6 mm/s, respectively. Control a single variable to combine different cutting thicknesses and feed rates. When the feed rate is 5 mm/s, the simulations of the cutting thickness taking six different sets of values are performed to discuss the effect of the cutting thickness on the force and temperature. When the cutting thickness is 0.03 mm, the simulations of cutting speeds taking six different sets of values are performed to discuss the effect of cutting speed on force and temperature. When the cutting thickness is set to 30 μm, and six sets of cutting speeds are taken. The relationship between cutting force and cutting speed is shown in Fig.12. Similarly, when the cutting speed is set to 5mm/s, 6 sets of cutting thickness values are taken, a single variable is controlled, and the simulations are sequentially performed by ABAQUS. When only the force at the time of stable cutting is taken, the relation between cutting force and cutting thickness is shown in Fig.13.
The temperature at different cutting thicknesses and cutting depths can be obtained by ABAQUS simulation, and the highest temperature under each cutting parameter can be obtained. Figure 14 is a diagram showing the temperature field distribution when the cutting speed of the abrasive grains is 5 mm/s and the cutting is stable under different cutting thicknesses. The relationship between the maximum temperature of bone grinding and the cutting thickness and cutting speed is shown in Fig. 15 and Fig. 16. The cutting temperature is the maximum temperature during the cutting simulation. Here, the initial temperature is 25°C.

(a) Abrasive grains and bone come into contact  
(b) Abrasive grain begins to cut bone

(c) Chip formation begins  
(d) Stable cutting

Fig. 10 Temperature distribution of single abrasive grain cutting. Where TEMP stands for temperature in degrees Celsius.
(a) Abrasive grains and bone come into contact
(b) Abrasive grain begins to cut bone
(c) Chip formation
(d) Stable cutting

Fig. 11 Stress distribution of single abrasive grain cutting. Where von Mises stress are given with the unit for MPa

Fig. 12 Relation between cutting force and cutting speed
Fig. 13 Relation between cutting force and cutting thickness
Fig. 14 Temperature field under different cutting thickness. Where the temperature is in degrees Celsius.
5.2 Simulation results of cutting force and temperature varying with osteon orientation

The bone is actually a heterogeneous biological material with a complex internal structure. In order to study the effect of osteon orientation on cutting force and cutting temperature, orthogonal cutting of bone is divided into three types according to the positional relationship between cutting direction and osteon orientation axis direction: cross cutting, parallel cutting and vertical cutting, as shown in Fig. 17.

Fig. 15 Relation between temperature and cutting speed
Fig. 16 Relation between temperature and cutting thickness

(a) Cross cutting
(b) Parallel cutting
(c) Vertical cutting

Fig. 17 Three directions of abrasive grain cutting
The steps for establishing the 3D simulation and the 2D simulation model are basically the same. The 3D model of the abrasive grain was first established. Considering the internal structure of the bone, a bone model including a osteon orientation, a matrix, and a cement line was established, and the elastic modulus was set to 26.3GPa, 20.8GPa, and 15.8GPa, respectively. Control a single variable, simulations under different cutting parameters were established to obtain simulation results of force and temperature in three cases for contrastive discussion. The cutting mode simulations in different osteon orientation directions are shown in Fig.18.

Fig. 18 Cutting mode simulations in different osteon orientation directions. Where von Mises stress are given with the unit for MPa
Figure 19 and Figure 20 show the variations of the cutting force with the cutting speed and the cutting thickness when the abrasive grain cutting direction is parallel, cross and perpendicular to the osteon orientation axis. Figure 21 and Figure 22 show the variation of the maximum temperature of parallel, cross and vertical cutting with cutting speed and cutting thickness.

Fig. 19 Relation between cutting force and cutting speed  
Fig. 20 Relation between cutting force and cutting thickness  
Fig. 21 Relation between the highest cutting temperature with cutting speed
5.3 Theoretical calculation and simulation results of single abrasive grain cutting force

Figure 23(a) and (b) are theoretical analysis and 2D finite element simulation results of the cutting force of a single abrasive grain, respectively. Figure 23(c) shows the change trend of the cutting force with the cutting speed during vertical, parallel and cross cutting, when considering the internal structure of the bone. Figure 24(a) shows the variation of the cutting force with the feed rate obtained by theoretical analysis. Figure 24(b) and (c) show the relationship between the cutting force and the cutting thickness obtained by finite element simulation.
Fig. 23 Comparison of theoretical calculation and simulation varying with cutting speed
6. Discussion

6.1 Influence of cutting parameters on cutting force and temperature

It can be seen from Fig. 10 that since the abrasive grains start to contact the bone, the temperature is continuously increased as the cutting progresses, and the temperature at the time of stable cutting reaches a maximum and fluctuates up and down around this value. Referring to previous studies, it was found that the thermal conductivity of bone is small, and heat is mainly concentrated in the cutting area. And in Fig. 10, the highest temperature is in the area of contact between the abrasive grains and the bone. Therefore, grinding damage is generally caused by the surface of the bone in orthopedic surgery, and the grinding temperature of the bone surface is the focus of research.

It can be seen from Fig. 11 that stress is generated when the abrasive grain is in contact with the bone block, and the stress range is further expanded as the cutting progresses. In Fig. 11, the stress contours are distributed in a circular arc shape, and are extended outward by layer, centering on the contact point of the abrasive grain and the bone. The
maximum stress is near the contact point and the stress value gradually decreases outward from the contact point. It can be seen from the simulation results that the distribution of the maximum value of stress and temperature is in the area where the abrasive grain contacts the bone. The value of the force is closely related to the temperature. The higher the force, the higher the temperature. It can be seen from the simulated stress distribution diagram that the stress fluctuates around a stable value during stable cutting.

It can be seen that the cutting force increases slowly with the increase of cutting speed and cutting thickness in Fig.12 and Fig.13. It is found from the simulation in Fig.14 that the temperature at which the abrasive grains are cut to the same position gradually increases with the increase of the cutting thickness, which is consistent with the change trend of the cutting force, indicating that the temperature and the force are closely related.

It can be seen from Fig.14 that the distribution areas of the temperature field and the highest temperature are different when the cutting thickness is different. When the cutting thickness is 10μm and 20μm, the highest cutting temperature is concentrated on the raised chips, and most of the heat generated can be carried away by the chips. When the cutting thickness reaches 30μm, the highest cutting distribution temperature range on the chips is relatively reduced and progresses to the bone surface. When the cutting thickness is 40μm, 50μm and 60μm, the maximum temperature distribution range is close to the cutting surface, and the highest temperature increases with the increase of cutting thickness. The cutting temperature of the bone is higher, the temperature difference is greater, and the range of thermal diffusion increases accordingly. But overall, there is not much heat transferred to the inside of the bone, which is consistent with the theory that the thermal conductivity of bone is small. Figure 16 is the relationship between temperature and time at a certain point on the abrasive grain during cutting. The temperature which is 25°C at the beginning of the cutting gradually increases as the cutting progresses and tends to be constant during stable cutting.

It can be seen in Fig.15 and Fig.16 that the cutting temperature increases as the cutting speed increases, and the cutting temperature is approximately proportional to the cutting speed. The cutting temperature increases with the increase of the cutting thickness, and the growth rate is relatively flat, which is consistent with the increasing trend of the cutting force with the cutting thickness. As the cutting speed and the thickness of the cutting increase, the amount of deformation of the bone increases, the force against deformation increases, the cutting force increases, and the amount of heat generated by the work of the force increases.

6.2 Effect of osteon orientation on cutting force and cutting temperature

It can be seen from the simulation in Fig.18 that when the abrasive grain cutting direction is parallel to the osteon orientation axis, the stress extends in a circular shape, and the stress concentration occurs in the contact area between the abrasive grains and the bone, which is similar to the 2D cutting. When the abrasive cutting direction intersects the osteon orientation, the stress increases and the range of stress on the bone extends. When the abrasive grain cutting direction is perpendicular to the osteon orientation axis, the stress first extends forward along the matrix, and the stress is distributed around the osteon orientation. Since the elastic modulus of the osteon orientation is larger than the cement line and the matrix, the crack is first generated at the cement line. Therefore, if the osteon orientation direction of the bone to be ground is known, the cutting force increases with the increase of cutting speed and cutting thickness. Under the same cutting conditions, the cutting force is the largest when the cutting direction is perpendicular to the osteon orientation, and the cutting force is the second when the cutting direction intersects the osteon orientation axis, and the cutting force is the smallest when the cutting direction is parallel to the osteon orientation axis. Therefore, if the osteon orientation direction of the bone to be ground is known, the cutting force perpendicular to the bone unit direction should be avoided as much as possible without affecting the surgical effect. In parallel cutting, the crack extends along the weaker cement line and eventually the osteon orientation fibers are peeled off, and the bone tissue undergoes a certain amount of slip along the cement line, which requires less energy, so the cutting force and cutting temperature are low. In cross-cutting, the cutting direction intersects perpendicularly to the long axis of the osteon orientation, which means that the cutting crack will be tangent to the osteon orientation and meet the boundary of the cement line, except directly through a single osteon orientation fiber. Due to the low strength of the cement line boundary, the cutting crack will expand along the cement line boundary around the osteon orientation fiber, and the entire osteon orientation fiber will be peeled off, so the force in the cross cutting mode is larger than the parallel cutting mode. In the vertical cutting, the strength and toughness of the bone are larger than the
parallel cutting and cross cutting due to the reinforcing effect of the unit fibers in the vertical direction, so the cutting force is the largest at this time.

It can be seen from the simulation in Fig.21 and Fig.22 that under the same cutting parameters, the maximum cutting temperature under vertical cutting is greater than the maximum cutting temperature under cross and parallel cutting, which is consistent with the cutting force. The failure of bone tissue during parallel cutting occurs mainly along the weaker cement line; the crack extends along the cement line and matrix during cross-cutting, and then the osteon orientation is peeled off. Compared with the other two cutting directions, due to the reinforcement of the osteon orientation fiber in the vertical cutting, the crack needs to accumulate more energy through the osteon orientation, so the temperature is higher than the temperatures of the other two cutting directions.

6.3 Comparison of theoretical calculation and simulation of single abrasive grain cutting force

It can be seen from the Fig. 23(a) and (b) that the change trend of cutting force is basically the same. The theoretical analysis results in that the cutting force increases with the increase of the rotational speed, and the finite element simulation results show that the cutting force increases with the increase of the cutting speed, which verifies the proportional relationship between the grinding tool rotation speed and the abrasive cutting speed. The theoretical analysis results show that the cutting force increases with the increase of the rotational speed, and the finite element simulation results show that the cutting force increases with the increase of the cutting speed, which verifies the proportional relationship between the grinding tool rotation speed and the abrasive cutting speed. Figure 23 (c) shows that when considering the internal structure of the bone, the change trend of the cutting force with the cutting speed during vertical, parallel and cross-cutting is consistent with the theoretical analysis results and the 2D simulation results. Although the cutting forces are different in the three cutting modes, the cutting force increases with the increase of the cutting speed, which is consistent with the theoretical analysis results. Through the theoretical analysis results, the 2D simulation results and the cutting force results of the 3D three cutting modes are compared, it is found that the overall change trend of the cutting force growth rate is consistent.

The greater the feed rate, the greater the cutting thickness of a single abrasive grain. It is found in Fig. 24 by comparison that the trend of the curve obtained by theoretical analysis, 2D simulation and 3D simulation is consistent. Theoretical analysis shows that the cutting force of a single abrasive grain increases with the increase of the feed rate. From the finite element simulation, it can be found that the cutting force of a single abrasive grain increases with the increase of the cutting thickness regardless of the internal structure or not, and the speed of the growth rate is fast and then slow. It is found that the theoretical analysis results and the finite element simulation results are consistent by comparison, and the correctness of the theoretical model of single abrasive grain cutting force is verified.

7. Conclusion

In this paper, the micro structure and composition of bones are analyzed, and the thermodynamic properties parameters of bones are given. The single abrasive grain model was reasonably simplified to facilitate the study, and a mathematical model of the single abrasive grain cutting force was established. A single abrasive grain cutting model was established by ABAQUS to observe the generation and distribution of force and temperature under different cutting parameters (cutting speed, cutting thickness), and to analyze the influence of cutting parameters on cutting force and cutting temperature. Based on the bone micro structure, a microscopic model of the bone (including the matrix, bond line, osteon orientation) is established. The relationship between the cutting force and the cutting parameters in the three cutting modes of vertical, cross and parallel is studied, which indicates that the cutting force of the abrasive increases with the increase of cutting speed and cutting thickness. The cutting force in the vertical cutting mode is the largest, the cutting force in the cross cutting mode is the next, and the cutting force in the parallel cutting mode is the smallest. Finally, the comparison between theoretical and simulation analysis shows that the theoretical analysis results are consistent with the finite element simulation results, which verifies the correctness of the theoretical model of single abrasive grain cutting force. What’s more, Micro cutting is the performance of macro cutting, they should have the same regularity. In order to verify the correctness of micro finite element simulation, macro cutting experiments will be carried out in the future to verify the influence of cutting parameters on cutting force and cutting temperature in the simulation conclusion. The single-factor variable method will be adopted to test bone cutting temperature through using artificial thermocouple thermometer based on bone cutting temperature test experimental platform.
However, there are also some shortcomings in our research. Bone cutting temperature depends on many factors. Bone is a heterogeneous anisotropic composite material. Its constitutive equation can not accurately reflect the physical properties of bone materials. In addition, the mechanical and thermodynamic properties of the different bone materials are not accurate enough without considering the differences in bone morphology and bone characteristics. How to build an accurate finite element simulation model by thoroughly analyzing and studying the bone microstructure and different type bone densities will be the future work. In the future, the influence of medium such as blood and coolant on cutting force and temperature should also be considered.

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