Cutting Behavior of Cortical Bone in Different Bone Osteon Cutting Angles and Depths of Cut

Yuanqiang Luo1,2, Yinghui Ren1*, Yang Shu1, Cong Mao2, Zhixiong Zhou1 and Z. M. Bi3

Abstract

Cortical bone is semi-brittle and anisotropic, that brings a challenge to suppress vibration and avoid undesired fracture in precise cutting process in surgeries. In this paper, a novel analytical model is proposed to represent cortical bone cutting processes. The model is utilized to predict the chip formations, material removal behavior and cracks propagation under varying bone osteon cutting angles and depths. Series of orthogonal cutting experiments were conducted on cortical bone to investigate the impact of bone osteon cutting angle and depth of cut on cutting force, crack initialization and propagation. The observed chip morphology highly agreed with the prediction of chip formation based on the analytical model. The curly, serrated, grainy and powdery chips formed when the cutting angle was set as 0°, 60°, 90°, and 120°, respectively. Cortical bone were removed dominantly by shearing at a small depth of cut from 10 to 50 μm, and by a mixture of pealing, shearing, fracture and crushing at a large depth of cut over 100 μm at different bone osteon angles. Moreover, its fracture toughness was calculated based on measured cutting force. It is found that the fluctuation of cutting force is suppressed and the bone material becomes easy to remove, which attributes to lower fracture toughness at bone osteon cutting angle 0°. When the cutting direction develops a certain angle to bone osteon, the fracture toughness increases then the crack propagation is inhibited to some extent and the fluctuation of cutting force comparatively decreases. There is a theoretical and practical significance for tools design and operational parameters choice in surgeries.

Keywords: Bone cutting surgery, Orthogonal cutting models, Anisotropic materials, Chip formation, Crack initialization and propagation, Fracture toughness

1 Introduction

Cortical bone cutting processes are very common in knee arthroplasties, dental implants and spine surgeries [1–3]. However, a bone cutting process exposes the risk of bone cracks. Such cracks cause an instable screw insertion [4] or instable cutting process in orthopedic robotic surgeries [5]. To predict a crack initiation and propagation, it is critical to investigate bone cutting behavior in a bone cutting process. While the cortical bone cutting behavior is a complex process due to its multi-scale structure. It consists of osteons (around 100 μm), harversian canals, interstitial lamellae, and boundaries of osteons and interstitial lamellas with the weakest bonds [6]. Therefore, the cortical bone appears an obviously anisotropic characteristic at various depths of cut and cutting directions.

Many researchers have studied three-dimensional (cutting direction across, parallel and transverse to the bone osteon orientation) bone cutting processes with the consideration of depth of cut. For example, Jacobs et al. [7] investigated how the depth of cut, tool rake angle, and bone orientation relative to cutting direction affected the chip formation to obtain in smooth and segmented chips. Malkin et al. [8] observed that the cortical bone was...
removed as chips due to fracture occurring at the cutting edge. Sugita and Mitsuishi [9, 10] analyzed the crack propagation and proposed a cutting technique to reduce cutting force and temperature. Liao and Axinte [11] investigated the condition of a transition condition from shear to fracture of material removals in a 3D orthogonal cutting model. Feldmann et al. [12] characterized the effect of the rake angle and the depth of cut on the cutting force, the temperature and the fracture of brittle bones. Bai et al. [13] rationalized the crack propagation and chip morphology at both of microstructure and sub-microstructure scales. The aforementioned studies confined the scope of investigation for depth of cut, rake angle, and three orthogonal cutting directions. Few work was reported on the bone cutting behavior of cortical bones in more than three cutting directions. Note that in a real orthopedic surgery, not all of cutting processes are performed along an orthogonal direction. For examples, a K-wire drilling insertion was performed obliquely to orthogonal directions [14]. A drill bit design for self-centering drill on inclined plane, is neither parallel nor transverse to the bone orientation direction strictly [15]. Cseke and Heinemann [16] argued that the cutting direction affected the drilling force and chip formation. Liao et al. [17] developed a cutting model to predict cutting force and temperature subjected to a given cutting angle in bone milling. Due to anisotropy of bone materials, a slight change of the cutting angle relative to the bone orientation may alter the mechanism of chip formation and crack propagation significantly. Therefore, it is of importance to investigate cutting behaviors with a certain cutting angle other than three orthogonal directions.

To understand bone cutting behavior, the properties of cortical bone materials, in particular, fracture toughness, must be characterized. Fracture toughness describes the ability of the material in resisting crack initiation and propagation. Limited works were reported on the investigation of fracture toughness of cortical bones in orthogonal cutting: Feldmann et al. [12] presented a bone fracture toughness model when the cortical bone was cut in a perpendicular direction. Bai et al. [18] compared the bone fractures in conventional and impact cutting and found that the impact cutting was able to reduce the fracture toughness of bones. Their conclusions were based on the assumption that the cutting direction was in one of three orthogonal directions. How to affect fracture toughness in more than three directions was not covered.

This work aims to develop a cutting analytical model subjected to different orthogonal directions and large depth of cut, which includes more possibilities in range of traditional orthogonal cutting angles to simulate the real surgery situation. The calculation model of fracture toughness was further derived based on energy balance principle to reveal the relationship between crack propagation and cutting angles in cortical bone cutting process. To validate the cutting analytical model, a series of cutting experiment was performed on fresh bovine femur bone, whose chip formation, cutting force and fracture toughness were discussed accordingly.

2 Chip Formation and Fracture Toughness in Different Bone Osteon Cutting Directions

To investigate the impact of cutting direction relative to bone osteon orientation, the cutting direction is described by a bone osteon cutting angle $\theta$ in Figure 1. In this section, in view of the anisotropic micro-structure of bone, bone osteon cutting angle $\theta$ is set as a discrete value of 0°, 60°, 90°, and 120°, respectively. The cutting scenarios are referred as mode #1, #2, #3, and #4, correspondingly. In mode #1 (Figure 1(a)), $\theta$ is set to 0°, and the cutting direction is parallel to the bone osteon orientation. In mode #2 (Figure 1(b)), $\theta$ is set to 60°, and the cutting direction is with an angle of 60° to the bone osteon orientation. In mode #3 (Figure 1(c)), $\theta$ is set to 90°, and the cutting direction is perpendicular to the bone osteon orientation. In mode #4 (Figure 1(d)), $\theta$ is set to 120°, and the cutting direction is with an angle of 120° to the bone osteon orientation.

Due to anisotropy and semi-brittle property of bones, the cortical bone is removed dominantly by shearing in a small depth of cut ranging from 10 to 60 μm. The chips are continuous in any cutting direction (Liao et al. and Bai et al. [11, 13]). Increasing the depth of cut over 100 μm, the cortical bone removal behavior will vary with the cutting direction because the bone cutting process is performed in the scale of osteons and Haversian canals. A new analytical model is needed to

![Figure 1](image-url)
investigate chip formation, crack initiation and propagation, cutting force, and fracture toughness in different cutting directions.

2.1 Mode #1 with a Bone Osteon Cutting Angle of 0°
In mode #1, the cutting direction is aligned with the bone osteon orientation. The cortical bone is removed along a cement line where the bone osteon and bone matrix are weakly joined. When a tool tip inserted into cortical bone with a horizontal cutting force, crack \( a_0 \) is initiated, and the crack \( a \) is stably propagated during the cutting process. The horizontal cutting force will accelerate the crack propagation along the cutting direction in Figure 2(a). The material removal is similar to peel a bone layer from the bone matrix, and the size of crack became \((a_0 + a)\).

The formed chip is simplified to a cantilever in Figure 2(b), and the chip is subjected to a bending moment by cutting forces \( F_n \) and \( F_c \) that results in peeling a bone layer from the bone matrix. With a continuous cutting, the chip turns to a curly morphology in Figure 2(c).

A simple fracture toughness model of cortical bone is derived based on this cutting model analysis and energy balance principle. Bone material is removed by the external force applied in the tool, which converts into the elastic strain energy and potential energy for bone fracture. The elastic strain energy is equal to potential energy for bone fracture [19].

Both of vertical and horizontal cutting force \( F_n \) and \( F_c \) contribute to elastic strain energy in the cutting process. The elastic strain energy by \( F_n \) is found as [20, 21],

\[
U_{F_n} = \frac{F_n^2 (a_0 + a)^3}{2E_1 I_1},
\]

where \( E_1 \) is elastic modulus along to the bone osteon orientation; \( I_1 \) is the area moment of inertia calculated as,

\[
I_1 = a_w h^3 / 12,
\]

where \( h \) is the depth of cut, \( a_w \) is the width of cut.

The elastic strain energy by \( F_c \) is found as,

\[
U_{F_c} = \frac{(F_c y)^2 (a_0 + a)}{2E_1},
\]

while \( y \) is the deflection at tip related to vertical cutting force \( F_n \) as,

\[
y = \frac{F_n a^2 (2a + 3a_0)}{6E_1}.
\]

Therefore, the total elastic strain energy \( U_1 \) in mode #1 is found as,

\[
U_1 = U_{F_c} + U_{F_n} = \frac{F_c^2 a^4 (2a + 3a_0)^2 (a_0 + a)}{72E_1^3 I_1^3} + \frac{F_n^2 (a_0 + a)^3}{2E_1 I_1}.
\]

Assuming that the required potential energy for fracture is equal to the elastic strain energy [19], fracture toughness \( G_1 \) in mode #1 is determined by the elastic strain energy as,

\[
G_1 = \frac{1}{a_w} \frac{dU_1(a)}{da} = \frac{F_c^2 a^2 (28a^2 + 96a^2a_0 + 105aa_0^2 + 36a_0^2)}{72a_w E_1^3 I_1^3} + \frac{3F_n^2 (a_0 + a)^2}{2a_w E_1 I_1}.
\]

The crack length is determined by [22],

\[
a + a_0 = \sqrt{\frac{\pi^2 E_1 I_1}{4F_c}}.
\]

In Eq. (6), since \( a_0 \) or \( a \) is very small, the first part can be ignored since the polynomial powers of \( a_0 \) and \( a \) are 6. The resulted value of the first part will be insignificant in comparison with the result of the second part. Substituting Eq. (7) into Eq. (6) simplifies the expression of the fracture toughness as,

\[
G_1 = \frac{3\pi^2 F_n^2}{8a_w F_c}.
\]
2.2 Mode #2 with a Bone Osteon Cutting Angle of 60°

In mode #2, the bone osteon cutting angle $\theta$ is 60°, the material is removed along the osteon orientation due to the weak strength at the cement line. The rake face of the tool pushes and deforms the bone as serrated chips, and then the shear angle tends to close to the bone osteon cutting angle $\theta$ [23, 24]. The cortical bone is removed away at the tool tip, which is similar to the case when a ductile metal was removed in a cutting process. As shown in Figure 3, the bone chip slips along the shearing direction and deforms as serrated morphologies.

For energy conservation, the total energy was from the work by the cutting force, and it was then converted into shear energy, friction energy and fracture energy.

The condition for energy conservation was expressed by Patel et al. [25] as,

$$ W = U_s + E_f + \Pi_1, $$

where $U_s$ was the shear energy, $E_f$ was the friction energy and $\Pi_1$ is the fracture energy in mode #2.

Eq. (9) could be deduced further as,

$$ \frac{\sigma_s}{2} \frac{h}{\sin \theta} = \left( \frac{F_c}{a_w} - G_2 \right) \cos \theta - \frac{F_n}{a_w} \sin \theta, $$

where $\sigma_s$ is the shear stress, $h$ is the depth of cut, $a_w$ is the width of cut, $G_2$ is the fracture strength, and $F_c$ and $F_n$ are cutting and thrust forces, respectively.

The fracture toughness is expressed as,

$$ G_2 = \frac{F_c}{a_w} - \frac{\sigma_s}{2} \frac{h}{\sin \theta \cos \theta} - \frac{F_n}{a_w} \tan \theta. $$

2.3 Mode #3 with a Bone Osteon Cutting Angle of 90°

The cutting direction is perpendicular to the bone osteon orientation in mode #3. The bone osteon will be bended and cracked by $F_c$ and the initialized crack is propagated by the effect of $F_n$ and $F_c$. In Figure 4(a), bone osteons are cut down by $F_c$ and the crack $a$ occurs to the cutting direction. Due to a weak strength at the cement line of bone, cracks will be initialized in this boundary by the thrust force $F_n$. Figure 4(b) shows the cutting and thrust force that are applied on a bone osteon, the cutting force mainly cut down the bone osteon and move it one by one. The removed bone osteons turn into grainy chips that are scattered over the bone surface showed in Figure 4(c). Therefore, the chips in mode # 2 have grainy and scattered morphology. The energy conservation principle is used to analyze a fracture toughness approximately.

The elastic strain energy $U_{F_n}$ by the thrust force is determined as [20, 21],

$$ U_{F_n} = \frac{1}{2} \frac{F_n^2 h}{E_3 A} = \frac{F_n^2 h}{2E_3 A}, $$

where $E_3$ is elastic modulus of bone osteon perpendicular to the cutting direction.

While the elastic strain energy $U_{F_c}$ by cutting force is expressed as,

$$ U_{F_c} = \frac{F_c^2 h^3}{2E_3 I_3}, $$

The elastic strain energy $U_3$ is expressed as,
Similar to the case in mode #1, the fracture toughness is calculated as,

\[ G_4 = \frac{U_4}{a_w a} = \frac{F_n^2 h}{2 a_w a E_3 A} + \frac{F_c^2 h^3}{2 a_w a E_3 I_4}. \]  

where \( \gamma \) is an angle of tool rake angle.

The elastic strain energy \( U_F \) by the thrust force is found as [20],

\[ U_F = \frac{F_n^2 h}{2 E_4 A}. \]  

where \( E_4 \) is the elastic modulus, \( A_4 \) is the area, and \( A_4 = a_w \times (d + d + a_p)/2 \).

The elastic strain energy \( U_F \) by the cutting force is [20],

\[ U_F = \frac{F_c^2 h^3}{2 E_4 I_4}. \]  

where \( I_4 \) is the area moment of inertia of the bone osteon calculated as,

\[ I_4 = \frac{a_w (d + d + a_p)^3}{12}. \]  

The energy conservation principle is used to estimate the fracture toughness. The crack length \( a \) in Figure 5(b) is calculated as,

\[ a_p = h[\cot (\pi - \theta) - \tan \gamma], \]

\[ a = a_p + d, \]

where \( \gamma \) is an angle of tool rake angle.

The elastic strain energy \( U_F \) by the thrust force is found as [20],

\[ U_F = \frac{F_n^2 h}{2 E_4 A}. \]

where \( E_4 \) is the elastic modulus, \( A_4 \) is the area, and \( A_4 = a_w \times (d + d + a_p)/2 \).

The elastic strain energy \( U_F \) by the cutting force is [20],

\[ U_F = \frac{F_c^2 h^3}{2 E_4 I_4}. \]

Finally, the fracture toughness \( G_4 \) is calculated as,

\[ G_4 = \frac{U_4}{a_w a} = \frac{F_n^2 h}{2 a_w a E_4 A} + \frac{F_c^2 h^3}{2 a_w a E_4 I_4}. \]

### 3 Experiments

To validate the proposed cutting model in predicting chip morphology and fracture toughness in these four bone osteon cutting direction, orthogonal cutting experiments were conducted with varying cutting angles and depths of cut. The cutting tests were repeated four trials for a combination of a specified depth of cut and bone osteon cutting angle in Table 1.

| Parameters                  | Value          |
|-----------------------------|----------------|
| Depth of cut \( h \) (µm)   | 10, 50, 90, 130|
| Bone osteon cutting angle \( \theta \) (°) | 0, 60, 90, 120 |
Due to the similar properties to human bones, bovine femur bones were commonly used in bone cutting experiments [27]. To prepare bone osteons for a cutting angle of 60° or 120°, fresh bovine femur bones were sawed to small pieces manually. Pieces were then grounded to produce bone blocks with an inclined face of a 60° angle. As shown in Figure 6(a), three machined faces were named as Face #1, #2 and #3, respectively. In each mode, the face with corresponding bone osteon orientation was set as cut face. To meet the condition of orthogonal cutting, the width of the cutter was wider than the width of bone sample. Thus, the bone block was sliced with a width of 1.5 mm in parallel to Face #1, #2 and #3, respectively. The tool had a width of 2 mm in Figure 6(b). The prepared bones were stored in refrigerator.

To acquire stable cutting forces and chip morphologies in four modes with a different depth of cut, a micro-cutting setup was used to perform orthogonal cutting experiments in Figure 6(c). Two active linear stages (Y axis and Z axis) (Model 200cri, Siskiyou Instrument) were mounted on the third active linear stage (X axis) (Model HLD 60, Moog Animatics). A precision micro-linear stage (Z’ axis) (Model Micro-Controle, Klinger) was mounted on the Z axis linear stage to provide precise feeding. The tool (Thinbit) had its rake and rear angles of 10° and 15°, respectively. It was clamped on the precision Z’ axis to conduct these experiments. The cutting speed was set as 0.5 mm/s. A prepared bone was taken from the refrigerator and immersed into saline for 2 h at room temperature, and was then clamped on the worktable by a step block clamp.

In addition, the micro-cutting system was equipped with (1) a piezoelectric dynamometer (Model 9256C, Kistler) to measure cutting forces, (2) a data recorder (Model DL750 ScopeCorder, Yokogawa) to record force data with the sampling rate of 2000 Hz, and (3) a digital microscope (Model 503+, Gaosuo) to catch chip morphologies under different cutting conditions as shown in Figure 6(c).

4 Experimental Results
4.1 Chip Morphologies

Figure 7 showed the variety of chip morphologies in mode #1 ($\theta = 0^\circ$): Figure 7(a) showed a continuous chip in a spiral shape under the depth of cut of 10 μm. Figure 7(b) showed a continuous chip in a curvy shape under the depth of cut of 50 μm. Figure 7(c) showed a serrated chip under the depth of cut of 90 μm, and Figure 7(d) showed a much curlier chip under the depth of cut of 130 μm.

Figure 8 showed various chip morphologies in mode #2 ($\theta = 60^\circ$): Figure 8(a) showed continuous chip shape, but the curly chip was not like Figure 7(a) with a spiral curly chip. With the increase of depth of cut (50 μm, 90 μm and 130 μm), it always showed a serrated chip, but its morphology is from slightly serrated to severely serrated in Figures 8(b), (c) and (d).

When the cutting direction was perpendicular to the bone osteon orientation, Figure 9(a) showed the continuous chip under the depth of cut of 10 μm. The chip became serrated when the depth of cut was set as 50 μm in Figure 9(b). The chip became discontinued when...
the depth of cut was set as 90 μm in Figure 9(c). At the depth of cut of 130 μm, the chip became large grainy as shown in Figure 9(d).

When the bone osteon cutting angle was set as 120°, the cutting direction was opposite to the bone osteon orientation. With a depth of cut of 10 μm, the chip in Figure 10(a) was still continuously but tended to be broken easily. With a depth of cut of 50 μm, the chip in Figure 10(b) became continuous. With a depth of cut larger than 90 μm, the chips in Figures 10(c) and (d) were crushed to powdery morphology.

4.2 Cutting Force

Figure 11 showed the cutting forces when the depth of cut was set as 10 μm in four cutting modes. Figures 11(a) and (b) showed that the horizontal and vertical cutting forces in mode #1 and 2 were relatively stable; while the cutting forces in Figures 11(c) and (d) for mode #3 and 4 showed obvious fluctuating.

Figure 12 showed the cutting forces when the depth of cut was set as 130 μm in four cutting modes. A cutting force was characterized as its static and amplitude components. Although the static horizontal cutting force in any of these four modes remained constant, the amplitude of horizontal cutting force was increased when the cutting angle was increased from Figures 12(a) to (d).

Figure 13 compared the static horizontal and vertical cutting forces in different depths of cut. The solid lines were fitted by linear least squares. From the scatter dots in the depth of cut of 10 μm, the mean horizontal forces exhibited the same changing trend and increased with an increase of the cutting angle or the depth of cut shown in Figure 13(a). The depth of cut and cutting angle also affect the static vertical cutting forces significantly as shown in Figure 13(b).

4.3 Fracture Toughness

The bone fracture toughness could be calculated based on the static components of cutting force from bone orthogonal cutting experiments in four modes. The elastic modulus in different bone osteon cutting angles is listed in Table 2. The shear stress $\tau$ in bone osteon cutting angle 60° is $6.7 \times 10^7$ N/m² [28]. Thus, according to Eqs. (8), (11) and (22) the values of fracture toughness
in different bone osteon cutting angles are calculated to 652 ± 184 N/m, 3105 ± 1310 N/m, 1695 ± 302 N/m and 1532 ± 149 N/m, respectively.

5 Discussion
When the depth of cut was set as 10 μm, there are continuous chips in cutting process at four bone osteon cutting angles. The cortical bone is removed by shearing during depth of cut in the bone fibrils arrays scale [5]. But these chips show a very small radius and tight curl morphology at bone osteon cutting angle 0°. At bone osteon cutting angle 60°, chips show a larger radius and stretches forward. At bone osteon cutting angle 90°, chips show a continuous morphology at tool tip and curl forward until breaking down. At bone osteon cutting angle 120°, chips show a small radius and easily break down. Due to anisotropy of cortical bone, these differentiated chip morphology phenomena attributes to different fracture strains of chips at four bone osteon cutting angles.

When the depth of cut is smaller than 20 μm, the horizontal cutting force is stable with less fluctuating shown in Figures 11(a) and (b). However, the cutting angle affects the fracture in sense that the tool needs to cut down the bone osteon in a transverse or even slightly opposite direction, this explained the light vibrations of horizontal cutting forces in Figures 11(c) and (d).

When the depth of cut was increased to 50 μm, the serrated chip indicates that the material is removed by shearing. This result agrees well with the conclusion in Refs. [11, 13] that the serrated chip happens when the depth of the cut was in the range of 20 μm to 60 μm. Based on the experimental results and theoretical models, shearing become the dominating material removal behavior when the depth of cut is set in this range. The bone osteon orientation mainly affects curling of chips and slightly affects the horizontal cutting force.

When the depth of cut was set over 100 μm, the cortical bone cutting behaviors were highly diversified. Taking an example of mode #1, a layered chip should be formed along bone osteon direction when the depth of cut (such as 130 μm) is at the scale of the diameters of osteons or Haversian canals (in Figure 14(a)) from the analytical model. Fortunately, a layered and curled bone chip was observed on the tool rake face in Figure 14(b). This bone removal behavior in this mode #1 could be viewed as peeling layered bone from the bulk materials. It could generate a high quality surface along this direction due to the curl chip formation (in Figure 14(b)) and stable force figure with time (in Figure 12(a)) [29].

In mode #2, the cutting angle affects the cutting behaviors significantly. The material is removed by shearing, which is totally different from the peeling behavior in mode #1. The serrated chip was observed since the tilted bone osteon formed a shear angle with the cutting direction. The rake face pushes the chip forward, meanwhile the materials are squeezed to make itself continuously stretched with the cutting process continuing. The chip develops serrated chip as shown in Figure 14(d).

In mode #3, the bone osteon cutting angle was set to 90°. On the one hand, the horizontal cutting force that

| Parameter                     | Value          |
|-------------------------------|----------------|
| Bone osteon cutting angle θ(°) | 0, 60, 90, 120 |
| Elastic modulus (x 10⁹ N/m²)  | 10.4 ± 1.64, 12.8 ± 1.57, 23.1 ± 3.18, 12.8 ± 1.57 |
mainly applies in the bone osteon to produce the main crack (Figure 4(c)). On the other hand, the vertical cutting force makes the cortical bone to produce a crack along the cement line with a weakest strength. So the grainy chips are generated (Figure 14(e)). The experimental result showed that the chip morphology in Figure 14(f) matched the results of theoretical analysis reported in Ref. [10]. Therefore, cortical bone is removed in mode #3 by fracture and formed grainy chips.

In mode #4, the bone material removal process experiences bending and crushing simultaneously (Figure 14(g)) when the bone osteon cutting angle was set as 120°. Different from the bone removal behavior in mode #3, the rake face of tool touches the bone osteon earlier than the tool tip. The rake face of cutting tool produces a press on the bone osteon, and then the tool tip generates a contact to bone osteon in proceeding the cutting process. The chip is crushed to power morphology as shown in Figure 14(h).

For the bone fracture toughness in mode #1, although the bone chip is peeling from the bone matrix, the material is fractured by an open mode [19]. While the fracture toughness was calculated to $652 \pm 184$ N/m. It is fairly close to the reported reference value $644 \pm 102$ N/m in Table 3. At present, few work reports the fracture toughness at bone osteon cutting angle 60°. For mode #2, it belongs to the shear mode fracture based on the analysis model of bone chip formation (Figure 3). According to Ref. [30], at bone osteon cutting angle 0° and 90° the reference value of fracture toughness is $1723 \pm 487$ N/m and $4710 \pm 1284$ N/m, respectively, in Table 3. According to Eq. (11), calculated value of fracture toughness is $3105 \pm 1310$ N/m at bone osteon cutting angle 60°, which is just within scope of the above reference value. In mode #3, the crack is produced perpendicularly to the bone osteon orientation, the fracture mechanism is an open mode, and the corresponding fracture toughness was $1495 \pm 302$ N/m. The deviation of fracture toughness is large since the cutting force is fluctuated sharply. The estimated fracture toughness is similar to the reported value $1532 \pm 149$ N/m [30]. In mode #4, few work is reported for the corresponding fracture toughness. Since the cutter is slightly opposite to the bone osteon orientation, the required cutting energy in this mode is larger than that in mode #3. The fracture toughness in model #4 was slightly larger than that in mode #3.

The largest fracture toughness was mode #2 in a shear mode fracture, followed by mode #4, mode #3, and mode #1 in open mode fracture. Figure 15 showed the correspondence of crack growth and propagation and amplitude of cutting force. The fracture toughness is associated

![Figure 14 Chip formations in depth of cut 130 μm](image)

Table 3 Fracture toughness value

| Fracture toughness | Bone osteon cutting angle |
|--------------------|--------------------------|
|                    | 0°           | 60°       | 90°       | 120°      |
| Calculated value (N/m) | 652 ± 184 | 3105 ± 1310 | 1495 ± 302 | 1532 ± 149 |
| Reference value (N/m) [30] | Open mode | 644 ± 102 | – | 1374 ± 183 | – |
| Shear mode       | 2430 ± 836  | – | 4710 ± 1284 | – |
with crack initiation and propagation. The lowest fracture toughness was mode #1. It meant that the crack easily propagated in mode #1. The crack is along the weak cement line in the cutting direction, and it produces a stable cutting force (see the enlarged view in the right of Figure 15(a)). For the shear mode fracture in mode #2, the crack is propagated hardly down to the next cement line of bone, because this bone osteon bears a shear force obliquely up to the next osteon. A long and deep micro crack cannot be produced in the next cement line, as arrowed shown in the left of Figure 15(b). But a tiny micro crack could occur due to the vertical cutting force. Since the micro cracks propagated speed is faster than cutting speed, when the tool tip approached nucleation location of micro crack, a vibration force occurs (see the enlarged view in the right of Figure 15(b)). In mode #3, the crack is initialized and propagated to the next bone osteon in advance. The direction of the crack propagation is perpendicular to the cutting direction as arrowed in the left side of Figure 15(c). When the cutter arrives here, it produces a highly vibrated cutting force (see the enlarged view in the right of Figure 15(c)), the amplitude of the horizontal force is larger than that in Figure 15(b). Since the fracture toughness is smaller than that in mode #2, it easily produces a vertical crack to the cutting direction. In mode #4, a crack propagates to the next bone osteon and then extends along the weak cement line, which is stretched in machined surface deeply. Since the rake face of tool touches the bone osteon with a horizontal force. This horizontal force accelerates the crack propagation along the cement line along the arrow shown in the left of Figure 15(d). When the tool arrives here, it produces more highly vibrated force (see the enlarged view in the right of Figure 15(d)).

In a summary, when the fracture toughness is small, and the crack is initialized and propagated along the cutting direction, it would produce a stable cutting force and result in high quality surface. In such an operating condition, the crack helps the material removal process. When the crack growth and propagation is not along the cutting direction, the fracture toughness is increased to suppress crack propagation, then it will produce a comparatively stable cutting force.

6 Conclusions

This work was motivated to optimize cutting parameters to suppress vibration and avoid undesired fracture in precise cutting processes in surgeries. In particular, the impact of the depth of cut and the cutting direction relative of bone osteon orientation on chip formation and fracture toughness were focused. The analytical models for four typical conditions were developed, and experiments were performed to show the effectiveness of the proposed models in predicting chip morphologies and cutting forces. It has been found that:

1. The chip morphology is affected by the cutting direction relative to the bone osteon orientation and the depth of cut greatly. With a small depth of cut, the chip is continuous, and the curl radius of chip varied with the cutting angle. With a large depth of cut, the chip morphology become curly, serrate, grainy and powdery when the cutting angle is set as 0°, 60°, 90°, and 120°, respectively.

2. The proposed cutting models and experimental results showed that the cortical bone cutting behavior is varied with the depths of cut and the cutting direction. In a small depth of cut up to 50 μm, the cortical bone is removed by shearing, and the
The aforementioned findings have this theoretical and practical significance in helping engineers to design orthopedic tools and optimize operational parameters in bone-cutting surgeries.

Author contributions
YL and YR designed experiments, acquired data and edited manuscript draft; YS assisted with experiments data analysis; CM, ZZ and ZB edited and supervised the manuscript. All authors read and approved the final manuscript.

Authors' Information
Yuanqiang Luo, born in 1990, is currently a lecturer at College of Automotive and Mechanical Engineering, Changsha University of Science and Technology, China. She received her PhD. Degree from Hunan University, China, in 2020. Her research interests include bio-material processing technology and medical device manufacturing. Tel: +86-18229075357, E-mail: yuanqiang@csust.edu.cn.
Yinghui Ren, born in 1979, is currently an associate professor at College of Mechanical and Vehicle Engineering, Hunan University, China. She received her PhD. degree from Hunan University, China, in 2009. Her research interests include precision processing technology and medical device manufacturing. Tel: +86-13548596452, E-mail: rebecca_ryh@hnu.edu.cn.
Yang Shu, born in 1990, is currently a PhD candidate at College of Mechanical and Vehicle Engineering, Hunan University, China. His research interests include precision machining and intelligent molding. Tel: +86-15675124936, E-mail: yshu@hnu.edu.cn.
Cong Mao, born in 1975, is currently a professor at College of Automotive and Mechanical Engineering, Changsha University of Science and Technology, China. He received his PhD. degree from Hunan University, China, in 2008. His research interests include precision processing technology of difficult-to-cut materials. Tel: +86-731-85258630; E-mail: macong315@aliyun.com.
Zhixiong Zhou, born in 1953, is currently a professor at College of Mechanical and Vehicle Engineering, Hunan University, China. E-mail: zhouzx8@hnu.edu.cn.
Z.M. Bi, born in 1975, is currently a professor at Department of Civil and Mechanical Engineering, Purdue University Fort Wayne, U.S.A. His research interest includes precision processing technology. E-mail: bz@pfwedu.

Funding
Supported by China Scholarship Council, the National Natural Science Foundation of China (Grant No. 52075161), Hunan Provincial Natural Science Foundation of China (Grant No. 2022J400488), and Changsha Municipal Natural Science Foundation of China (Grant No. 2022cjk017).

Availability of data and materials
The datasets supporting the conclusions of this article are included within the article.

Competing interests
The authors declare no competing financial interests.

Author Details
1College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China. 1Hunan Provincial Key Laboratory of Intelligent Manufacturing Technology for High-performance Mechanical Equipment, Changsha University of Science and Technology, Changsha 410114, China. 1Department of Civil and Mechanical Engineering, Purdue University Fort Wayne, Fort Wayne, IN 46805, USA.

Received: 10 February 2021 Revised: 2 July 2021 Accepted: 14 June 2022 Published online: 14 July 2022

References
[1] D Axinte, Y B Guo, Z R Liao, et al. Machining of biocompatible materials – recent advances. CIRP Annals – Manufacturing Technology, 2019, 68: 629–652.
[2] Z H Chen, Y Zhang, C Y Wang, et al. Understanding the cutting mechanisms of composite structured soft tissues. International Journal of Machine Tools and Manufacture, 2020, 161(3):103685.
[3] J A Robles-Linares, D Axinte, Z R Liao, et al. Machining-induced thermal damage in cortical bone: Necrosis and micro-mechanical integrity. Materials and Design, 2021, 197:109215.
[4] M Hollenstein, S Sandriesser, E Bliven, et al. Biomechanics of osteoporotic fracture fixation. Current Osteoporosis Report, 2019, 17: 363–374.
[5] L Bai, J X Yang, X H Chen, et al. Medical robotics in bone fracture reduction surgery: A review. Sensors, 2019, 19: 3593-3612.
[6] E A Zimmermann, M E Launey, R O Ritchie. The significance of crack resistance curves to the mixed-mode fracture toughness of human cortical bone. Biomaterials, 2010, 30(11): 5297–5305.

[7] C H Jacobs, M H Pope, J T Berry, et al. A study of the bone machining process-orthogonal cutting. Journal of Biomechanics, 1974, 7: 131–156.

[8] K L Wiggins, S Malkin. Orthogonal machining of bone. Journal of Biomechanics Engineering, 1978, 100(3): 122-130.

[9] N Sugita, M Mitsuishi. Specifications for machining the bovine cortical bone in relation to its microstructure. Journal of Biomechanics, 2009, 42(16): 2826–2829.

[10] N Sugita, T Osa, R Aoki, et al. A new cutting method for bone based on its crack propagation characteristics. CIRP Annal - Manufacturing Technology, 2009, 58(1): 113–118.

[11] Z R Liao, D A Axinte. On chip formation mechanism in orthogonal cutting of bone. International Journal of Machine Tools and Manufacture, 2016, 102: 41–55.

[12] K L Wiggins, S Malkin. Orthogonal cutting of cortical bone: Temperature elevation and fracture toughness. International Journal of Machine Tools and Manufacture, 2017, 118–119: 1–11.

[13] W Bai, L M Shu, R L Sun, et al. Mechanism of material removal in orthogonal cutting of cortical bone. Journal of Mechanical Behavior of Biomedical Materials, 2020, 104.

[14] A Feldmann, P Ganser, L Nolte, et al. Orthogonal cutting of cortical bone: Temperature elevation and fracture toughness. International Journal of Machine Tools and Manufacture, 2017, 118–119: 1–11.

[15] W Bai, L M Shu, R L Sun, et al. Improvements of material removal in cortical bone via impact cutting method. Journal of Mechanical Behavior of Biomedical Materials, 2020, 108.

[16] T L Anderson. Fracture mechanics: fundamentals and application. 3rd ed. USA: CRC Press, 2005.

[17] Z R Liao, D A Axinte. Towards understanding the cutting and fracture mechanism in ceramic matrix composites. International Journal of Machine Tools and Manufacture, 2017, 118–119: 12–25.

[18] L X Chen, K F Zhang, H Cheng, et al. A cutting force predicting model in orthogonal machining of unidirectional CFRP for entire range of fiber orientation. The International Journal of Advanced Manufacturing Technology, 2017, 89: 833–846.

[19] H Li, X D Qin, G Y He, et al. Investigation of chip formation and fracture toughness in orthogonal cutting of UD-CFRP. The International Journal of Advanced Manufacturing Technology, 2016, 82: 1079–1088.

[20] Y Patel, B R K Blackman, J G Williams. Determining fracture toughness from cutting test on polymers. Engineering Fracture Mechanics, 2009, 76: 2711–2730.

[21] P Raibe, A H Burstein. The elastic and ultimate properties of compact bone tissue. Journal of Biomechanics, 1975, 8: 393–403.

[22] P L Huang, J F Li, J Sun, et al. Vibrational analysis in milling titanium alloy based on signal processing of cutting force. The International Journal of Advanced Manufacturing Technology, 2013, 64: 613–621.

[23] Z D Feng, J Rho, S Han, et al. Orientation and loading condition dependence of fracture toughness in cortical bone. Materials Science and Engineering C, 2000, 11(1): 41–46.