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IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International
Journal of
Integrated
Engineering

Frequency-Driven Crack Propagation in Ultrasonically-Assisted Bone Cutting

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DOI: https://doi.org/10.30880/ijie.2022.14.08.014
Received 30 May 2022; Accepted 28 November 2022; Available online 21 December 2022

Abstract: Ultrasonically-assisted bone cutting with high precision has many advantages for orthopedic surgeries. However, irregular crack propagation, large fractured chips, and surface damage may occur during the cutting process due to the brittleness and anisotropy of cortical bone. These can be minimized by optimizing the operating parameters of the cutting tool; cutting frequency, amplitude, speed, depth, and temperature, in consideration of the toughening mechanism of bone. Therefore, the current study is motivated to investigate the effect of varying frequency on crack propagation in ultrasonically-assisted bone cutting through the means of finite element analysis. The pattern of crack propagation in relation to the variation of frequencies was investigated using the extended finite element method (XFEM) in consideration of the bone microstructures. The results showed that crack propagation is effectively controlled when the tool is operated at higher frequencies, but an up-forward crack propagation following the trajectory of tool vibration is only apparent at frequencies higher than 800 Hz. Neglecting the operating outputs at 2400 Hz, the induced force and stress are observed to decrease proportionally with increasing frequency.

Keywords: Crack-propagation, XFEM, ultrasonically-assisted cutting, vibration frequency, bone microstructure

1. Introduction

In Malaysia, osteoporotic hip fractures are relatively common with 500 incidences per 100,000 population for individuals over 75 as of the year 1997 [1]. This incidence would certainly require an orthopedic surgery for joint fixation or arthroplasty. In orthopedic surgeries, bone resection is a common, yet technically challenging procedure as the precision of the cutting process would affect the postoperative results and recovery of patients. Many conventional cutting tools are crude, and the force and thermal issues still cannot meet the surgical requirement and remain the prime concern of orthopedic surgeons. The unnecessary levels of cutting force and induced heat may lead to large-scale fracture and surface damage of the bone that eventually hinders postoperative healing, and to the extreme, causes bone breakdown and osteonecrosis [2]. Some studies have reported that the critical temperature threshold for the onset of thermal bone necrosis is 47 °C [3-5].

To minimize invasiveness and improve the operation safety, the ultrasonically-assisted cutting (UAC) technique that applies high-frequency vibration has been alternatively used in bone resection as it is known for allowing high cutting precision. However, postoperative trauma such as microcracking and fractured chips may still occur due to the anisotropic property of bone and its hierarchical microstructure that contribute to its intrinsic toughening mechanism. Previous studies have shown that bone fracture and crack propagation are significantly dependent on the anisotropic properties of bone microstructure [6-12]. The cement lines were found to be able to deflect the incoming crack to protect the nerve tissues inside the Haversian canal, which is referred to as the bone primary toughening mechanism [12]. However, the

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*Corresponding author: menorwahida@usm.my bone toughness had been reported to decrease at high strain rates as cracks cannot be deflected and thus penetrate the osteons [10].

Previous studies found that the anisotropic behaviour of the bone significantly influences the orthogonal cutting process, such as the chip morphology and cutting temperature [13-14]. While sharing a relatively similar principle with that of UAC, Sugita and co-workers [2, 15] developed vibration-assisted tools for bone-cutting based on fracture characteristics of bone. On top of reporting the performance improvement of the techniques, the studies also provided some insights on how fracture mechanism (i.e., chip formation and crack propagation) reflects the overall performance of the cutting process. For example, one of the studies confirmed that the application of high vibration frequency increases strain rate that in turn, decreases the toughness of the bone, which consequently controls the direction of crack propagation effectively. The study also observed an upward crack propagation when the vibration frequency is over 800 Hz. These findings were quantified respectively by low surface roughness (Rz) value and small chip formation that could prevent the occurrence of large-scale fracture of the bone [2].

Hence, it can be deduced that there is a unique relationship between the operating vibration and bone fracture control that demands further investigation. In the present study, this unique relationship is examined by looking at the pattern of crack propagation concerning the varying operating frequency, which can be optimized accordingly for an efficient UAC procedure in bone resection.

2. Bone Cutting Model

2.1 XFEM for Crack Model

Crack-propagation in response to bone cutting at the microscale was modeled explicitly using the extended finite element method (XFEM) with the cohesive segments approach that involved defining two damage criteria; the crack initiation and the crack evolution criteria. Theoretically, the crack initiation begins when its criterion is satisfied to cause the enriched elements to separate into two divisions through a cohesive surface. Following the initiation, the crack grows, conforming to the crack evolution law, specified in terms of the fracture energy per surface area. It defines the energy required to degrade the intact cohesive surfaces to become completely open and traction-free crack surfaces. In the present study, the maximum principal strain criterion (MAXPE) was used as the crack initiation criterion for the bone microstructure constituents as a strain-based yield criterion has been commonly used to describe the fracture behavior of hard biological tissue [16]. Based on this criterion, it is assumed that a crack is initiated when the critical value of the maximum principal strain is reached. Both damage criteria used in this study are presented in Table 1.

2.2 Model Geometries and Material Properties

The analysis of crack-propagation in this study focuses on the bone cutting along its longitudinal axis, which is the most common cutting direction during orthopedic surgeries. A two-dimensional finite element model for bone was constructed in consideration of its microstructure using 4-node bilinear elements (CPE4) provided in the finite element code Abaqus 6.12 [17]. The microstructure model of the bone consisted of four main composite constituents, which were Harversian canal, interstitial matrix, osteon fibres, and cement lines that were represented in radial orientation, as shown in Fig. 1. The dimension of the entire model was 700 um x 500 um (width x height), reflecting a micro-scale area. The geometrical parameters of the constituents were defined based on a statistical analysis of real bone microstructures [7]. As magnified in Fig. 1, the elements at the surface where are in contact with the tool blade were made more refined to capture the definite variation of field quantities within the contact surface region.

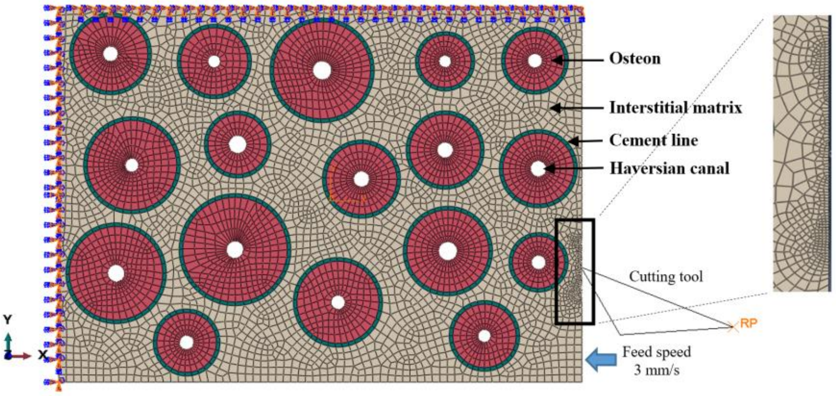


Fig. 1 - Finite element model of bone microstructure

The composite constituents were idealized as linear isotropic elastic materials with material properties assigned based on experimental data published in Li, et al. [18], as listed in Table 1. The crack initiation strain and fracture energy were defined according to those of reported in Abdel-Wahab, et al. [19]. The cutting vibration was simulated in the feed direction (y-direction) as schematically illustrated in Fig. 2, which was controlled by displacement boundary conditions given as:

$$x(t) = vt$$
$$y(t) = A_y sin(2\pi ft + \phi_y) \tag{1}$$

where x and y are the tool displacement in x- and y-directions; A_y is the thrust directional vibration amplitude, $\omega = 2\pi f$ is the angular frequency, wherein f is the tool vibration frequency, v is the feeding speed, and ϕ is the vibration phase shift. The top and left edges were fixed from moving in all directions, as shown in Fig. 1.

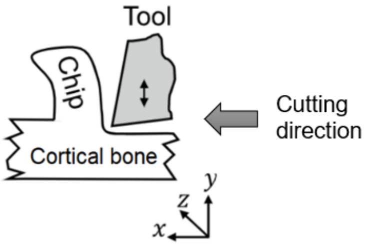


Fig. 2 - Vibration is superimposed in the feed direction of cutting tool

Table 1 - Material properties of bone microstructure constituents [18]

	Osteon	**Interstitial Matrix**	**Cement line**
Elastic modulus (GPa)	12.85	14.12	9.64
Poisson’s ratio	0.17	0.153	0.49
Fracture initiation strain (MAXPE)	0.65%	0.65%	0.65%
Evolution criterion -Fracture energy (N/mm)	0.86	0.238	0.146
Density (ton/mm^3)	2 x 10^{-9}	2 x 10^{-9}	2 x 10^{-9}

The present study examined the effect of four different UAC operating vibrations, 200, 800, 1200, and 2400 Hz, on the pattern of crack propagation in bone resection. The crack propagation pattern at zero vibration frequency, representing conventional cutting, was also evaluated for comparison purposes. For simplicity, the blade of the cutting tool was modeled as a rigid body with the feed speed of 3 mm/s. The vibration amplitude and cutting depth were set constant at 10 μm and 150 μm, respectively, in all analyses.

3. Results and Discussion

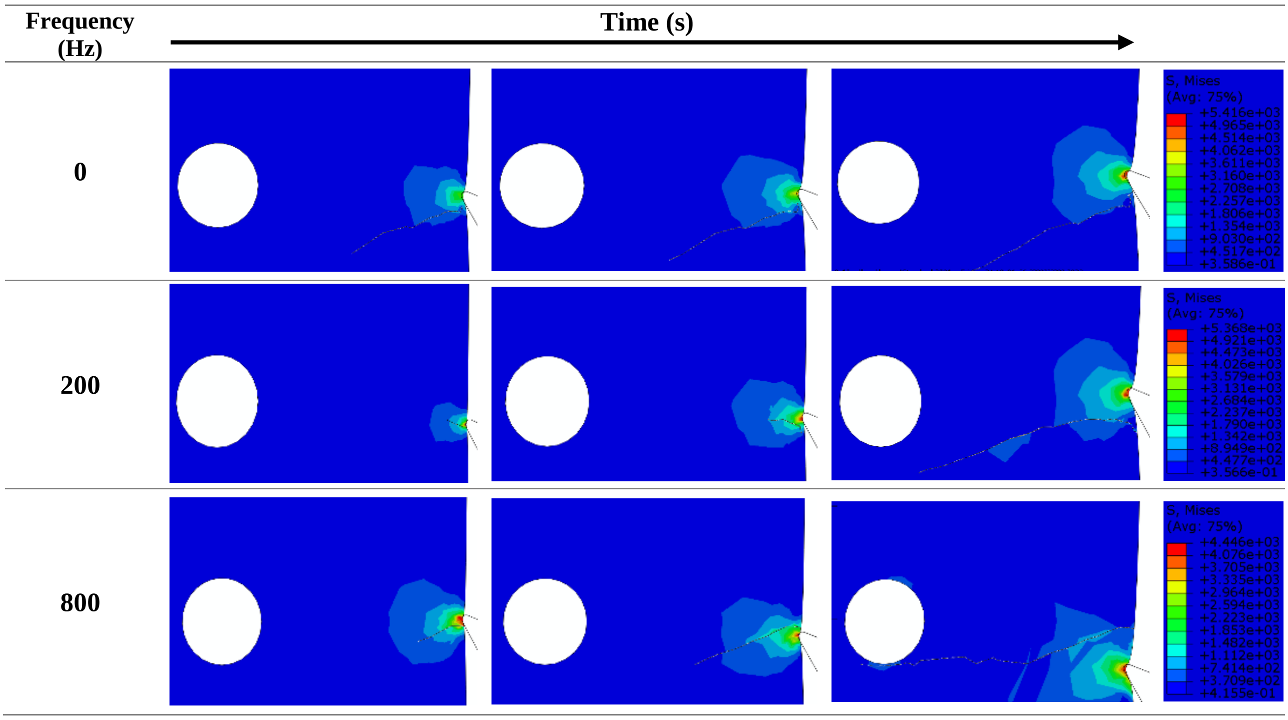
3.1 The Pattern of Crack Propagation

It is hypothesized that the crack propagation direction in cortical bone resection could be regulated by the trajectory of the ultrasonic vibration, in which the crack would enter the osteon because of the high strain rate induced by high-frequency vibration during the cutting. This notion is based on the principle of ultrasonic cutting where high-frequency vibration is superimposed on the cutting tool movement. The contact between the cutting tool and bone will initiate a crack, which then grows along the vibration trajectory of the cutting tool. In an elliptical-assisted vibration where vibration is applied in both tangential and feeding directions, a chip will be generated when the tool swings along the upward trajectory of the feeding vibration and detaches from the bone [2]. Based on this principle, relatively similar mechanisms of crack-propagation and chip formation are believed to occur in the current study with the application of longitudinal-assisted vibration.

As illustrated in Fig. 3, the patterns of crack initiation and propagation vary with the vibration frequency of the cutting tool. At zero frequency, the crack appears to have been deflected by the cement line to be propagating downward and away from the Haversian canal located directly ahead of the bone-tool contact point. As the time increases, the crack continues to grow down-forward, which could cause large fracture and major surface irregularity. When the vibration frequency is increased to 200 Hz, the crack initially appears to grow straight from the bone-tool contact point before it eventually deviates downward and penetrates the cement line and osteon but grows a little away from the canal as the time increases. This behavior is contrary to the pattern observed at 800 Hz, in which a downward crack trajectory is seen at the early stage of propagation before the crack grows relatively straight towards the Haversian canal as the time increases. At higher frequencies of 1200 and 2400 Hz, the crack appears to grow upward immediately after the cutting tool is in contact with the bone and continues to grow in this path with time. However, within the same time span, the crack at 2400 Hz grows longer and farther from the bone-tool contact point to penetrate the cement line and osteon and towards the Harversian canal. From these observations, it can be inferred that an up-forward crack trajectory following the longitudinal vibration becomes apparent when the frequency is over 800 Hz. However, the crack only infiltrates the cement line and osteon at higher frequencies, i.e., at 2400 Hz in the present study. This finding is inconsistent with the findings of Shu and Sugita [2], which showed similar crack propagation patterns but at lower frequencies in an elliptical-assisted vibration cutting. This discrepancy essentially signifies the influence of the tool vibration's directional property on the crack propagation pattern.

3.2 Cutting Force & Stress

As shown in Fig. 4, the induced forces appear to decrease gradually with increasing vibration frequency. This finding is agreeable with many studies [2, 15, 20] that reported the reduction in induced force with the application of mechanical vibration, which would subsequently minimize the postoperative risk. However, as seen in the figure, there is a sudden increment of force at the highest frequency examined, 2400 Hz with only 2% of force reduction from that induced in the conventional cutting (zero frequency). The highest cutting force reduction is seen at 1200 Hz with a reduction percentage of 33%. Another operating output that receives less attention is cutting stress, which is one of the primary mechanical factors in bone remodeling by stimulating the bone cells. As it is of particular importance in tool penetration and cutting, the shear stress induced by the vibrational impact load immediately after the cutting tool hits the bone at different frequencies is evaluated in this study. As shown in Fig. 5, the stress level varies insignificantly with increasing frequency, which is relatively consistent with that reported by Alam, et al. [21], who found no variation of peak stress with varying frequency. However, at 2400 Hz, the stress peaks up drastically, which could be explained by the high cutting force induced at this frequency.



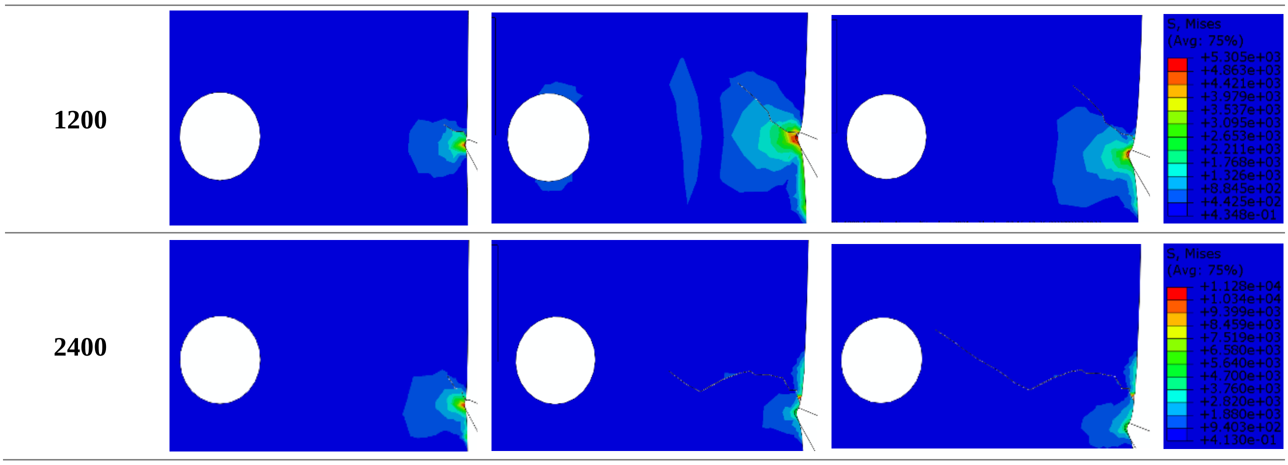


Fig. 3 - The time-variation of crack propagation patterns at five different vibration frequencies of cutting tool

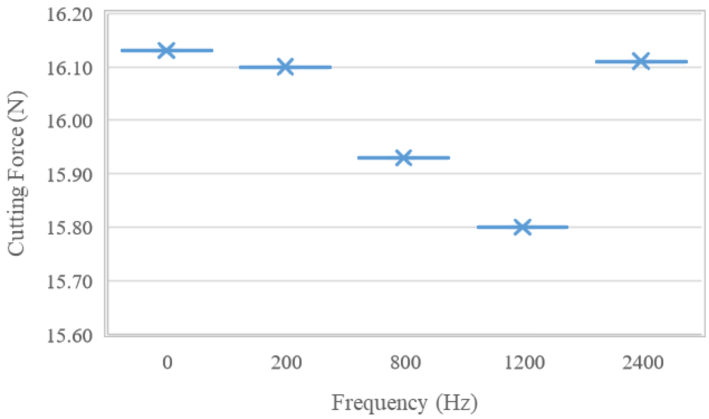


Fig. 4 - The induced cutting force in relation to the imposed frequency

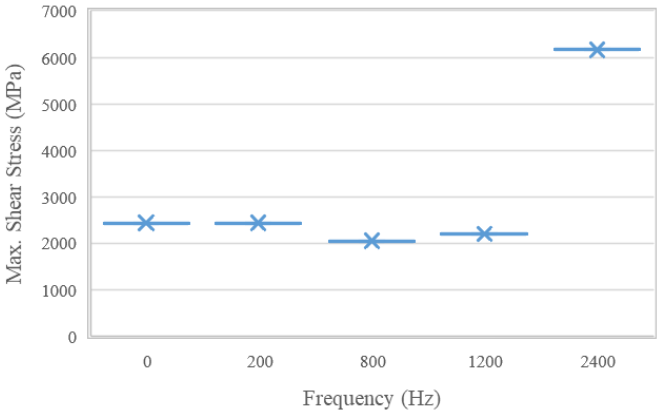


Fig. 5 - The variation of induced shear stress at the tool-bone contact point with respect to the imposed frequency

4. Conclusion

In orthopedic surgeries, an optimized set of UAC cutting parameters should be determined to ensure a precision cutting, which is important for minimizing postoperative trauma. In this study, XFEM has been used to examine the effect of varying frequencies of UAC on the pattern of crack-propagation in bone resection in consideration of the bone microstructures. The results confirm that the application of high frequency alone may essentially control the tool penetration and crack propagation. An up-forward crack path following the applied longitudinal vibration is observed at frequencies over 800 Hz and appears relatively ideal at 2400 Hz. However, at the latter frequency, a significant increment of induced cutting force and stress is observed, which does not conform to the principle of vibration-assisted cutting. Therefore, the optimum operating frequency in bone resection remains uncertain, and its determination requires further investigation.

Acknowledgement

The authors would like to acknowledge the support from the Ministry of Higher Education Malaysia under the Fundamental Research Grant Scheme: FRGS/1/2021/TK0/USM/02/15.

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