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Novel surgical machining via an impact cutting method based on fracture analysis with a discontinuum bone model

Naohiko Sugita (2)*, Liming Shu, Takehiro Shimada, Masaya Oshima, Toru Kizaki, Mamoru Mitsuishi (1)

School of Engineering, The University of Tokyo

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ABSTRACT

Cutting (including sawing and drilling) is a common procedure in orthopedics. Although it is widely used, cutting is associated with surgical problems, such as bone breakthrough and necrosis. In this study, the phenomenon of large fractures was analyzed with a discontinuum model of a bone by initially predicting crack propagation. A cutting method utilizing impacts by vibration was then proposed, and experiments were performed. The results indicated that the principal cutting force decreased by more than 80% in each cutting direction. The findings suggest that the method can realize low load, high efficiency, and high accuracy of bone machining.

1. Introduction

Bone cutting is a surgical procedure that is conducted often in the orthopedic and neurosurgical fields. As shown in Fig. 1, the cortical bone can be considered as a type of unidirectional reinforcement fabric, composed of several parts, such as the osteon and interstitial organs. The diameter of the osteon is approximately 100 μm, with the Haversian canal at its center. The osteon runs almost parallel to the longitudinal axis, and a lamellar system called the interstitial organ fills the gap among osteons.

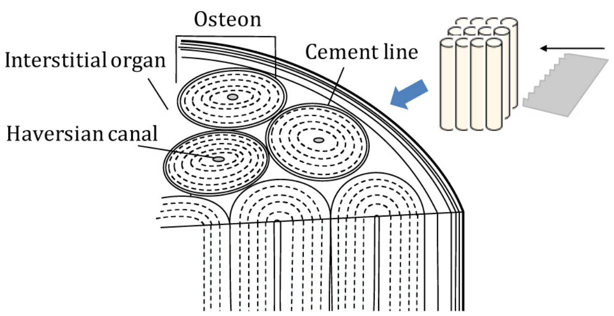

Fig. 1. Structure of cortical bone.

Bone is anisotropic in nature. Therefore, the cutting direction is critical. Three directions – parallel, across, and transverse – are defined in the osteon appropriately for this purpose. In addition, there are three main requirements for the machining of bones: high efficiency, high accuracy, and low temperature. High efficiency is required to reduce the operation time and the physical risk to the patient. In addition, high precision is important to obtain a good postoperative result. Furthermore, the cutting temperature must be maintained to prevent cell necrosis. Additionally, large-scale fracture and thermal damage are major problems faced during bone machining. It is difficult to satisfy these requirements simultaneously. Hence, new cutting methods and tools are required.

There are many studies on the processing of biomedical materials. Some of these studies have reported the relationship between bone tissue, tool shape, and the machining performance. Some tried to suppress the heat generation. Others observed the cutting phenomenon during processing. For example, Enomoto et al. proposed a grinding wheel that reduces heat generation [1]. Shih et al. reported the temperature prediction and cooling effects during bone grinding [2,3]. They also proposed the use of grinding wheels to remove calcified plaque [4]. Lucas et al. reported the cutting temperature during ultrasonic machining of wood and bone [5]. The authors have also observed the cutting phenomenon during bone machining, and proposed a crack control cutting method [6]. The result indicated that the influence of the microstructure in the bone tissue is significant. Therefore, it is necessary to propose a cutting method considering the relationship between the microstructure and the crack propagation.

This paper proposes an impact cutting method to reduce the mechanical load based on the analysis of crack behavior using a discontinuum bone model. In the proposed method, the experimental results showed that the principal cutting force decreased by more than 80% with the impact amplitude being 20 μm in each cutting direction. This suggests that the impact cutting method can realize lower load and higher efficiency of bone machining and is suitable for bone cutting.

2. Method

2.1. Fracture analysis during bone machining

According to a previous report [6], the cracks are often deflected and removed as large chips. Typically, the length of a crack varies.

* Corresponding author. Tel.: +81 358 416 356

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Thus, the influence of cracks is significant but has not been clarified. Therefore, the crack behavior in the bone tissue was analyzed first.

A bone model was developed considering its microstructure, as shown in Fig. 2. The differences in the mechanical properties of the microstructure will influence the crack propagation. The mechanical parameters of each microstructure were determined based on a previous study [7] and are listed in Table 1. The osteon and the interstitial organ occupy most of the cortical bone, and the study had indicated that the amount of elastic energy released by the crack growth in the osteon was nearly four times higher than that released in the interstitial organ. The diameter of the osteon is determined by the probability density function shown in Eq. (1), where the variables are determined as σ=35.3 μm,μ=99.9 μm based on the study [7].

$$f_{hs}(x) = \frac{sech\left\{\frac{\pi(x-\mu)}{2\sigma}\right\}}{2\sigma} \quad ,(1)$$

where $sech(x)$ is given by Eq. (2),

$$sech(x) = \frac{1}{\cosh(x)} = \frac{2}{e^{x} + e^{-x}} \quad .(2)$$

In addition, the diameter of the Haversian canal is obtained using the probability density function shown in Eq. (3), where k = 1.52, α = 2.7, β = 12.7μm, γ = 3.3μm from the study [7].

$$\frac{\alpha k\left(\frac{x-\gamma}{\beta}\right)^{\alpha k-1}}{\left\{1+\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right\}^{k+1}} \quad .(3)$$

The thickness of the cement line is 3 μm. The osteon, including the cement line and the Haversian canal, is randomly placed until it occupies 60% of the total area.

XFEM (eXtended FEM) was adopted as an analytical method for crack propagation. XFEM treats the discontinuity of the crack as an approximate function by using the shape function of the finite element method. XFEM does not require a remeshing method. That means to prevent fragmentation and complication of meshes, and the method is efficient for the crack propagation analysis. Bone damage criterion is based on the research by Emer [8].

The result of the Mises stresses is shown in Fig. 3. The stress concentration is high at the cutting edge and the Haversian canal.

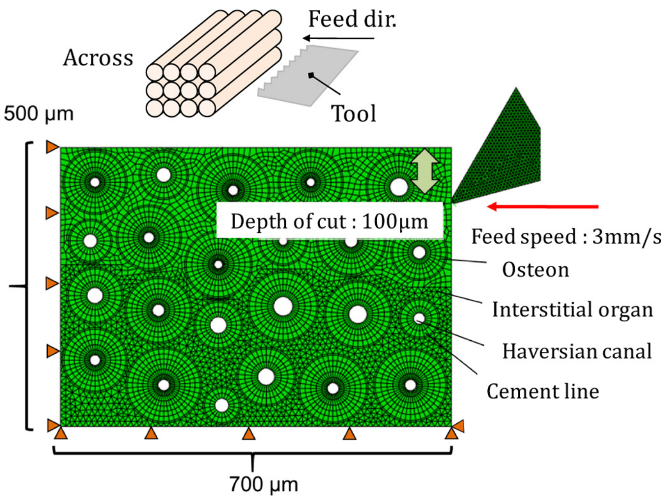

Fig. 2. Modeling of cortical bone.

Table 1
Mechanical properties of each component.

	Osteon	Interstitial organ	Cement line
Elastic ratio [GPa]	20.7	22.8	6.85
Poisson ratio	0.18	0.162	0.48
Fracture strength [MPa]	134.5	148.1	39.0
Elastic energy release ratio [J/m^2]	860	228	146
Density [kg/m^3]	2000	2000	2000

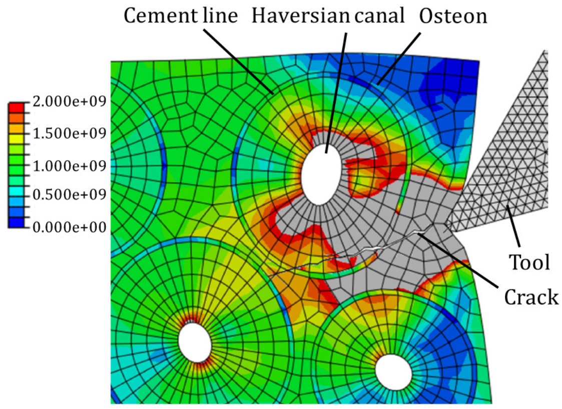

Fig. 3. Mises stress during bone machining.

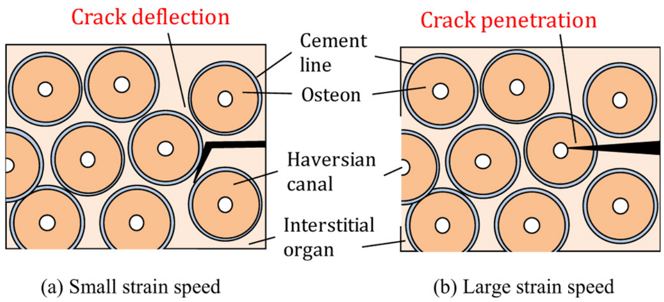

Fig. 4. Assumption of crack propagation.

On the other hand, the stress distribution at the cement line is smaller owing to its low elastic modulus. In this case, after the crack penetrated the osteon, it stopped at the cement line of another osteon.

As shown in Fig. 4, it is assumed that when the strain rate is high enough, the crack penetrated the osteon, but when the strain rate is small, crack growth stops at the cement line or the interstitial interface boundary. Bone has viscoelasticity and complicated microstructures. Therefore, the strain rate greatly influences the crack propagation. As the strain rate increases, the elastic energy release rate at the cement line and the intervening tissue increases. This implies that the difference in the elastic energy release rate at the osteon becomes small, thereby suppressing the crack deflection at the tissue boundary. By increasing the strain rate, it is considered possible to prevent the crack deflection at the tissue boundary.

2.2. Proposal of impact cutting to bone material

The impact cutting method shown in Fig. 5 is introduced based on the analysis in the previous section. It is expected to prevent large-scale fracture by generating small cracks to penetrate the osteon. After the cutting tool collides with the workpiece with impact, the

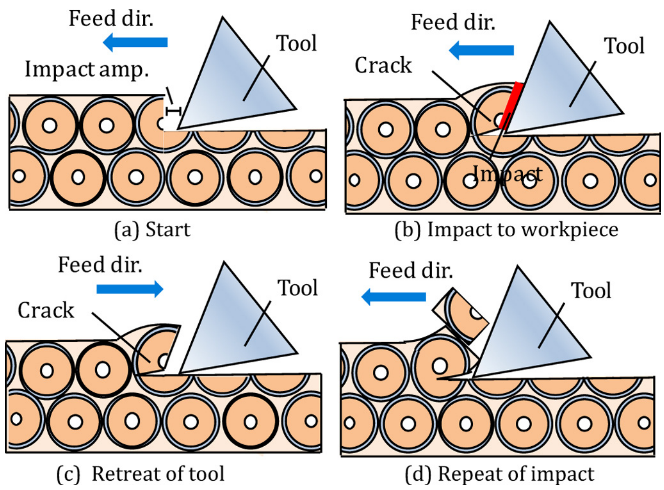

Fig. 5. Impact cutting method for bone material.

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