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Multi-grooved cutting tool to reduce cutting force and temperature during bone machining

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ABSTRACT

The cutting temperature of a cutting tool are required to be low during bone machining for preventing damage to bone cells. However, conventional tools are practically the same as those used for metal cutting, and many operational limitations have been reported. In this study, a dedicated cutting tool was designed for reducing cutting force and temperature. A short contact between the workpiece and the cutting edge leads to a reduction in the cutting force. Furthermore, a straight-line edge improves surface roughness. The effectiveness was evaluated using bovine bone, and the cutting force was found to be decreased by about 40%.

1. Introduction

With the aging of society, the number of arthropathy patients has increased in recent years. When arthropathy becomes severe, arthroplasty is conducted. In this surgical procedure, the bone is cut to fit the shape of an artificial joint that is implanted into the body. The main requirements for bone machining are high efficiency, high accuracy, and low cutting temperature. During arthroplasty surgery, the time available for bone machining is less than 15 min. The linear and angular accuracy requirements for the machined shape are 2 mm and 2°, respectively. The cutting temperature should be less than 50 °C. The cutting tools and devices currently used in arthroplasty are similar to those used in metal cutting. The result of the operation depends on the skill of the surgeon; therefore, new machining methods and devices are required. Cortical bone has an anisotropic structure, and we need to consider its characteristics in the design of a cutting tool [1].

We have previously proposed a crack control method that avoids tissue damage by decreasing the cutting temperature and cutting force [2]. By controlling the generation of brittle cracks and decreasing the cutting force, the processing energy will also be decreased. It is expected that this method can prevent surface degradation due to the formation of brittle cracks.

The purpose of this study is to develop a cutting tool to achieve high efficiency, high accuracy, and low cutting temperature during bone machining. A new concept for bone machining is evaluated in all feed directions of an anisotropic material, and the results are incorporated into the design of the cutting tool. A revised tool shape is proposed to reflect the results, and the effectiveness of the cutting tool is evaluated.

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The features of the tool we have developed are as follows: (1) roughing and finishing are carried out in rotation and (2) the cutting tool is serrated to reduce cutting energy. The proposed tool is expected to produce a precise surface and decrease the cutting load and temperature.

2. Concept of the cutting method for bone

2.1. Characteristics of cortical bone machining

The cutting mechanism to be used in bone machining depends on the depth of cut. For example, when the depth of cut is in the range of 10–30 μm, a chip is generated continuously, as shown in Fig. 1a. When the depth of cut is around 100 μm, cracking dominates the process, as shown in Fig. 1c [3].

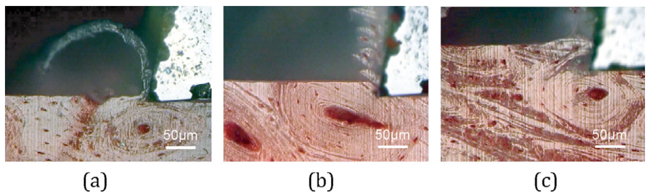

Fig. 1. Cutting type of bone machining [3] (depth of cut: (a) 10 μm, (b) 50 μm and (c) 80 μm, perpendicular direction).

Cortical bone is composed of fibers called osteons, and is an anisotropic material. Hence, the machining characteristics of cortical bone depend on the feed direction. Fig. 2 shows the relationship between feed and osteon directions during end milling. There are three feed directions: perpendicular, parallel, and transverse. Regarding the relationship between osteon orientation and feed direction, the cut direction is constant in

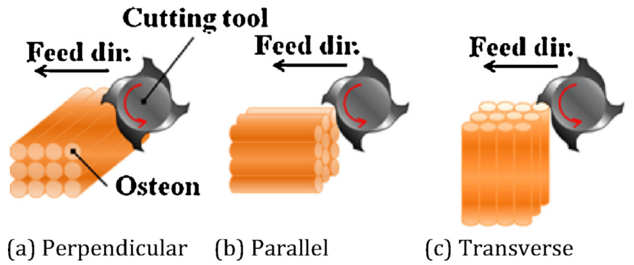

Fig. 2. Definition of cutting direction.

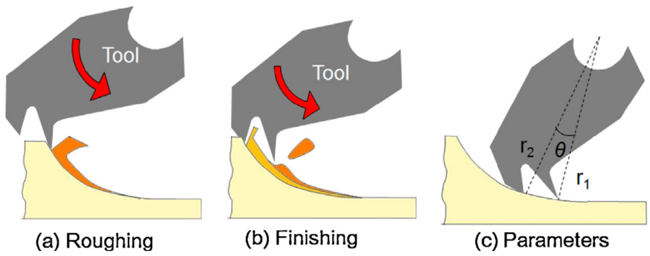

Fig. 3. Cutting process and structure of proposed tool.

the perpendicular direction. However, it varies for a rotating cutting tool in the parallel and transverse directions.

2.2. Basic concept of an end mill for bone machining

Fig. 3 shows the proposed cutting method for end milling of bone. The cutting tool has two types of edges for roughing and finishing. The first edge, shown in Fig. 3a, is used for roughing by brittle fracture dominated cutting. The second edge then finishes the surface by continuous chips. The roughing and finishing processes are performed with a rotating tool. The edge radii (r_1 and r_2) and the edge interval (θ) are the main parameters, as shown in Fig. 3c. The tool radius for finishing (r_2) is slightly larger than that for roughing (r_1). Small cracks are removed from the surface by the finishing process.

The edge radii (r_1 and r_2) and the edge interval (θ) were determined by considering the relationship between the depth of cut and chip formation (Fig. 1), and the duration of the operation. The cutting conditions were calculated to conform to the available time for machining during the arthroplasty operation (tool feed rate: 3 m/min, tool rotational speed: 10,000 rpm, depth of cut: 1 mm) and to satisfy the requirements for surface roughness. The feed rate parameters per tooth for roughing (f_1) and finishing (f_2) can be expressed based on geometric relationships by using the following equations:

$$f_1 = \frac{S}{nZ} - f_2 \quad \text{and} \tag{1}$$

$$f_2 = \sqrt{r_2^2 - (r_2 - d)^2} - \sqrt{r_1^2 - (r_1 - d)^2} + \frac{\theta S}{360n}, \tag{2}$$

where S is the feed rate, n is the rotational speed, Z is the number of edges, and d is the depth of cut in the radial direction. The undeformed chip thickness varies during rotation. The maximum chip thickness influences the cutting mechanism, and the parameters are set so that the chip formation is as expected, i.e., brittle fracture dominated or continuous chip cutting. The maximum chip thickness, h_{max}, is expressed as

$$h_{max} = f \sin\delta \quad \text{and} \tag{3}$$

$$\delta = \cos^{-1}\left(\frac{r-d}{r}\right), \tag{4}$$

where f is the feed per tooth (f_1 or f_2), d is the depth of cut in the radial direction, and r is the radius of the cutting tool.

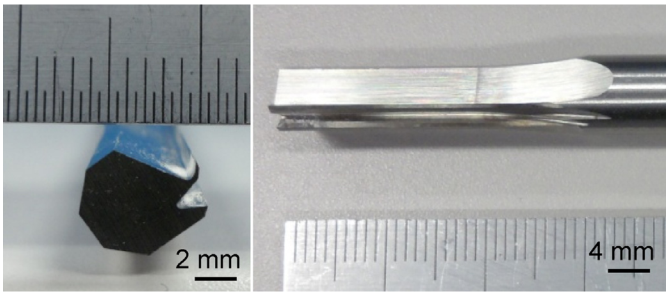

Fig. 4. Proposed cutting tool.

Based on these equations, the tool parameters were determined as follows: r_1 = 3.975 mm and r_2 = 4.0 mm, with an edge interval θ = 40° to allow for chip evacuation. In addition, we conducted experiments to determine the tool rake and clearance angles that influence machinability. We found that the ideal rake angles for the proposed tool were 50° for roughing and 10° for finishing. The clearance angle was set to 12° for both edges.

Fig. 4 shows the cutting tool as manufactured. The tool has one pair of flutes just for evaluation, and the edges of the cutting tool are straight with a helix angle of 0°. The tool material is stainless steel SUS420J2, which is well suited for biomedical use.

2.3. Experimental setup and cutting conditions

We conducted experiments with the proposed tool. The cutting conditions were listed in Table 1. The experimental setup is shown in Fig. 5. A dynamometer (Kistler, 9256A1), and a high-speed camera (Keyence, VW6000) were used for the measurements. The emissivity of bone was 0.98, and a thermography (NEC-Sanei, TH51) was used for temperature measurement. The cutting speed was lower than that assumed in Section 2.2, but the feed per tooth was set alike.

Table 1
Experimental conditions.

Cutting speed	15.8 m/min, 630 rpm
Feed per tooth	50, 150, 250, 350 μm
Radius of end mill	4.0 mm
Axial depth of cut	3.0 mm
Radial depth of cut	0.5 mm

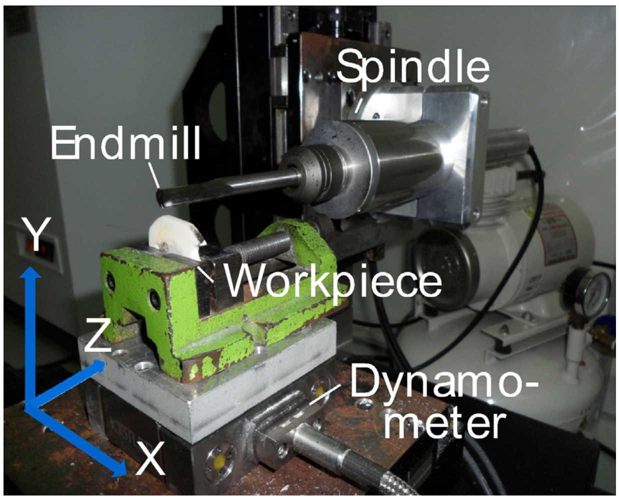

Fig. 5. Experimental setup.

2.4. Performance of the proposed tool

The performance of the proposed cutting tool was evaluated. The results were compared with those of a conventional tool, which has one straight edge and the same tool parameters. A bovine diaphysis was used as a workpiece.

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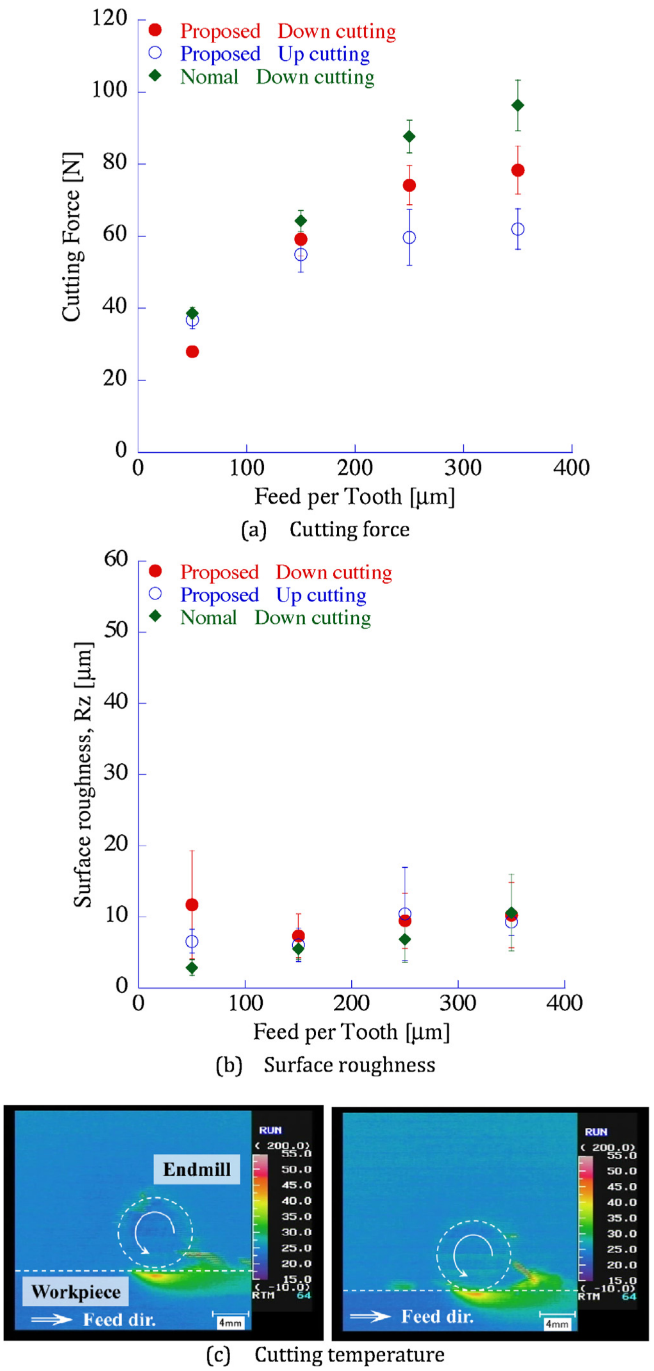

Fig. 6. Experimental results (parallel direction).

Fig. 6 shows the experimental results for parallel direction. The cutting force was reduced with the proposed tool, in comparison to a conventional tool (tool radius 4.0 mm, rake angle 10°, clearance angle 12°, helix angle 0°, material SUS420J2). Based on observation of the cutting process, the cutting edge slips slightly at the beginning of the roughing process in the downward part of the cut. This results in the increased depth of cut during finishing, causing degradation of the surface. We expected a decrease in cutting temperature owing to the decrease in cutting energy. However, no significant difference was observed. The pocket for cutting chips in the proposed tool is smaller than that in a conventional tool, which should improve chip evacuation.

To sum up, the cutting force was reduced for all osteon directions, for both upward and downward cutting. The cutting temperature and the surface roughness needed improvement. As described in the next section, the design of the cutting edge was revised to further reduce the cutting temperature.

3. Proposed slotted cutting tool

3.1. Revised design of the cutting edge

From the results in Section 2.4, it was found that the cutting force should be further reduced. If the contact length between the workpiece and cutting edge is shortened, as with a serrated cutting tool, the cutting force can be decreased, although the surface roughness is degraded. A surgeon performs bone cutting with only one tool during an arthroplasty operation. This means that the surface roughness must be improved even with a serrated tool. Therefore, we propose a cutting tool with serrated and straight edges, as shown in Fig. 7.

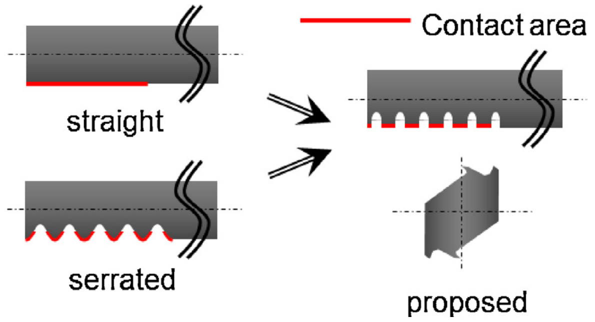

Fig. 7. Proposed cutting tool.

To finish the surface precisely, each edge has to have some phase shift. When the cutting tool finishes a rotation, the expected machining result can be accomplished. If the length of the serrated edge is too short, the stiffness of edge is reduced, and chipping will occur. The parameters of the cutting edge should be thus optimized.

The parameters of the cutting tool are shown in Fig. 8a: the pitch of the edge p, edge width e, and edge length l. The cutting areas for each edge are shown in Fig. 8b. Each edge has many cutting areas, and the workpiece is divided into small pieces. The undeformed chip thickness h in the red cutting area of Fig. 8b is expressed by Eq. (5). The cutting force and temperature can be simulated using this thickness.

$$h(z)=\begin{cases}\dfrac{S}{nZ}-\left(\sqrt{r_2^2-(r_2-d)^2}-\sqrt{r_1^2-(r_1-d)^2}+\dfrac{\theta S}{360n}\right) & \text{if } 0<z<e-\dfrac{1}{2}p\\[2ex] \dfrac{S}{nZ} & \text{if } e-\dfrac{1}{2}p<z<\dfrac{1}{2}p\\[2ex] \dfrac{S}{nZ}-\left(\sqrt{r_2^2-(r_2-d)^2}-\sqrt{r_1^2-(r_1-d)^2}+\dfrac{\theta S}{360n}\right) & \text{if } \dfrac{1}{2}p<z<e\\[2ex] 0 & \text{if } e<z<p\end{cases}, \quad (5)$$

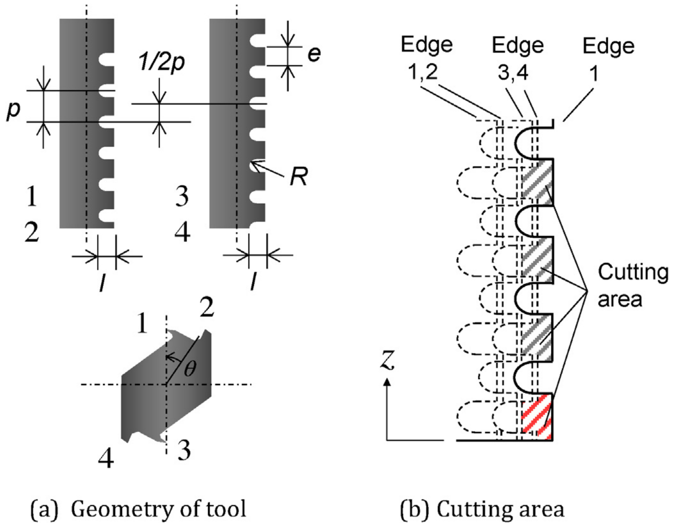

Fig. 8. Parameters of cutting tool.

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Table 2
Parameters of cutting tool.

Pitch *p*	1.4 mm
Edge length *l*	0.6 mm
Edge width *e*	0.8 mm
Round at bottom *R*	0.3

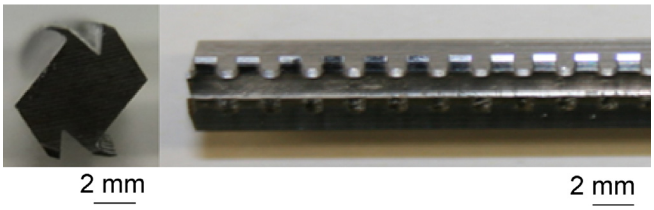

Fig. 9. Manufactured tool with nicks.

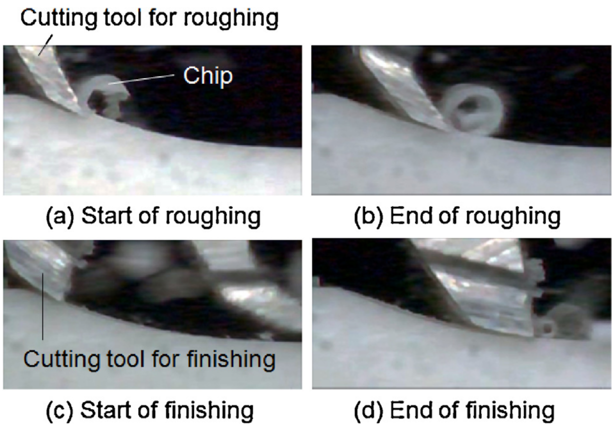

Fig. 10. Cutting phenomenon (parallel direction).

The parameters r_1, r_2, d, θ, S, n, Z are the same as in Eqs. (1) and (2). Each edge is divided into small segments, and an orthogonal cutting model is applied to the segments. The total cutting energy is calculated by integrating the force at each segment.

The parameters of the cutting tool are listed in Table 2. These parameters were selected to avoid chipping of the tool, and to reduce the cutting force and temperature. The other parameters are same as those in Section 2.2. Fig. 9 shows the tool as manufactured. The helix angle is set to zero to evaluate the basic performance. The tool material is stainless steel SUS420J2.

3.2. Machining performance of the proposed cutting tool

Experimental setup and cutting conditions are same as those in Fig. 5 and Table 1. Examples of cutting phenomena are shown in Fig. 10. The feed direction is parallel. First, the roughing edge begins machining with a large depth of cut, as shown in Fig. 10a and b. Then, the surface is finished by the finishing edge with a small depth of cut, as shown in Fig. 10c and d. Based on observation by high speed camera, the cutting tool performed as expected in all feed directions.

The experimental results for cutting force, temperature, and surface roughness are shown in Fig. 11. The feed per tooth was changed from 50 to 350 μm. The resultant cutting force is shown, and the feed direction is perpendicular. The cutting force was reduced by about 40% in comparison to a conventional tool as the feed rate was increased. This means that we can increase the

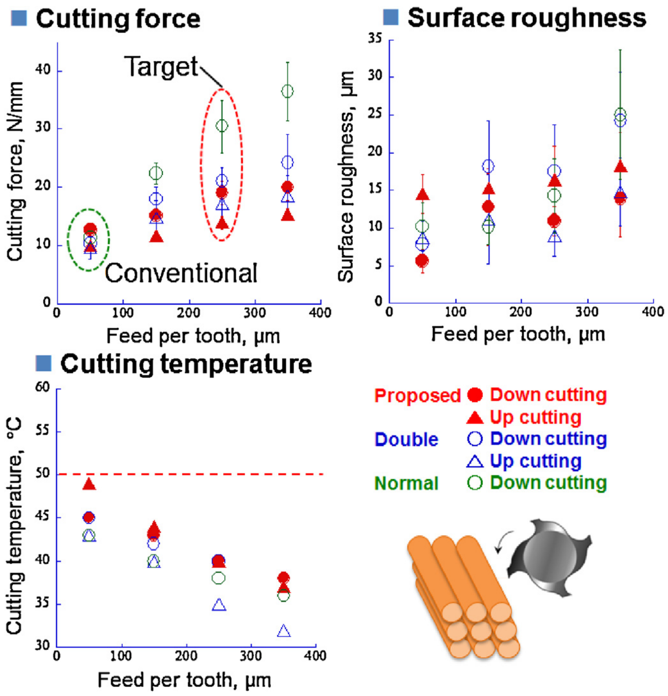

Fig. 11. Experimental results (perpendicular direction).

cutting speed for bone with the proposed tool. The machining accuracy was also improved. Regarding the cutting temperature, we did not find a significant decrease in the maximum temperature, but the size of the heat-affected area was reduced. The effectiveness of the proposed cutting tool was confirmed in other feed directions as well.

4. Conclusion

The results of this study are as follows:

(1) A concept for bone machining was proposed on the basis of microscopic cutting characteristics. The effectiveness was evaluated in all feed directions: perpendicular, parallel, and transverse. It was found that the cutting force was reduced in comparison to a conventional tool.
(2) A revised cutting tool was proposed. The revised cutting tool design has serrated and straight edges. The performance was evaluated, and the cutting force was reduced by about 40% with a high feed rate. The improved processing efficiency will contribute to the reduction of cutting temperature.

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