Cutting Tool for Bone Machining to Carry Out Roughing and Finishing in a Single Pass

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Abstract:
In orthopaedic surgeries involving bone excision, processing damage and excision accuracy strongly influence the postoperative results. Thermal damage from cutting heat causes necrosis of bone cells and should ideally be avoided. In this study, we propose a cutting tool with two types of cutting edges that avoids tissue damage by decreasing cutting force and temperature. By controlling the generation of brittle cracks and finishing the surface with small depth of cut, it is expected that the processing energy can decrease and the precise surface will be also obtained with our method.

Keywords: Bone cutting, Cutting tool, Crack free, End milling

1. Introduction

Cutting damage and excision accuracy strongly influence postoperative results in orthopedic surgeries. Thermal damage due to cutting heat causes necrosis of bone cells, and therefore, should ideally be avoided. Furthermore, bone machining devices need to be highly efficient because limited time is available for bone excision operations. Therefore, developing a new cutting method that solves these problems is necessary.

Currently, a bone saw is commonly used for cutting bones. However, the heat generated during cutting causes problems such as necrosis of the bone tissues and poor dimensional accuracy of the machined surface. Therefore, it is necessary to develop a new cutting method that solves these problems.

Several fundamental studies have been carried out on bone cutting from a viewpoint of cutting force measurement and have been reported [1][2][3]. However, it is expected that a new processing method is proposed for determining the practical excision conditions during surgeries and preventing the mechanical or thermal damage to bones.

According to our research results thus far, when cutting cortical bone at depths of cut less than 20 μm, a semi-continuous-type chip form was observed, accompanied by a high cutting force. When the depth of cut was large, e.g., 80 μm, cutting chips were formed by the propagation of brittle cracks [4], accompanied by surface damage; however, the cutting force per unit volume tended to be rather small [5].

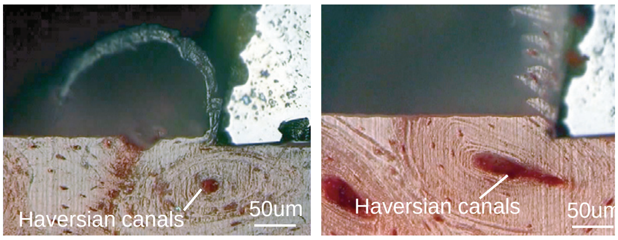
In this study, the authors propose a new cutting tool using a crack control method that avoids tissue damage by decreasing cutting temperature and cutting force. By controlling the generation of brittle cracks and decreasing the cutting force, it is expected that the processing energy will also decrease. Our method can therefore prevent surface degradation due to the formation of brittle cracks. The effectiveness was evaluated by some experiments with cortical bone of bovine.

2. Proposal of Cutting Method and Tool

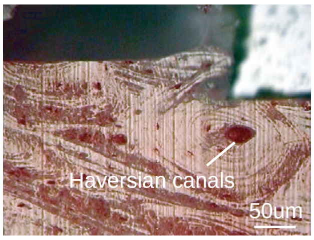
2.1 Cutting Method

According to our studies thus far, when crack-type chips are generated by brittle fractures, the required cutting force decreases, as compared to other processes that generate flow- and shear-type chips as shown in Fig.1 [5]. This implies that the processing energy required for machining is lower, and it is assumed that internal heat generation in the workpiece also decreases.

From the above assumption, it is possible to propose a cutting method to generate a crack intentionally. The behavior of crack propagation under a force was examined by microscopic observations. The influence of anisotropy in bone cutting can be discerned from the observation of crack generation and propagation in two-dimensional cortical bone cutting.



(a) Depth of cut : 10 um (b) Depth of cut : 50 um



(c) Depth of cut : 80 um

Figure 1: Chip form (cutting tool: diamond byte, tool rake angle: 10 deg., workpiece: bovine cortical bone, cutting direction: tangential, cutting speed: 10 μm/s).

The cutting tool for bone machining proposed in this paper has two modes for roughing and finishing in a single pass, and decreases the machining loads such as cutting force and temperature. In the bone cutting with the proposed rotational tool, large area is removed with low energy owing to brittle crack, and surface is finished precisely with small depth of cut as shown in Figure 2.

Cutting tool is fed forward while rotating, and the process is started with the cutting edge for roughing. Crack is generated by mechanical impact, and the area surrounded by cracks is removed as a chip ((a) in Fig.2). Then, the next process is started with the cutting edge for finishing ((b) in Fig.2), and the surface is finished precisely with the small depth of cut ((c) in Fig.2). Thus, two edges with different diameter conduct the roughing and finishing processes, respectively.

2.2 Cutting tool

Cutting tool was developed with the proposed method as shown in Fig. 3. In the study, the manufactured tool has one straight edge for analysis and observation. The main feature of proposed tool is the edge structure to realize two modes of roughing and finishing in a single pass.

It is necessary to determine the appropriate parameters such as the radius of edge r_1 and r_2 and the edge interval for the proposed cutting tool as shown in Figure 4. The parameters were determined from the relation between depth of cut and chip formation (Fig. 1) and the available time for the operation. For example, the cutting conditions were calculated to meet the available time for machining (tool feed rate: 3 m/min, tool rotational speed: 10000 rpm, depth of cut: 1 mm) and to satisfy the surface roughness.

As the result, the tool parameters were determined as follows: the radius r_1=3.975 and r_2=4.0, and the edge interval θ=40° in consideration of the chip evacuation. In addition, some experiments were conducted to determine the tool rake and clearance angles that influenced the machinability. From the results of experiments, the rake angles of proposed tool were set to 10° for finishing and 50° for roughing. The clearance angle was set to 12° in both edges.

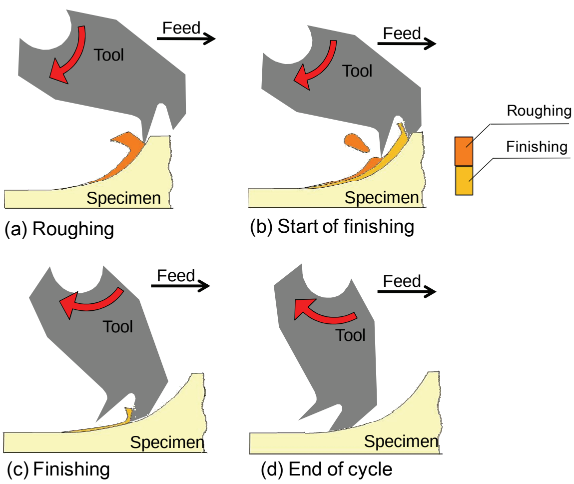
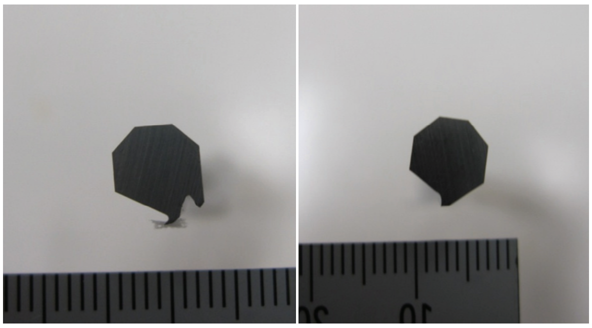


Figure 2: Proposed cutting method.



(a) Proposed tool (b) Conventional tool

Figure 3: Cutting tool (material: SKH51, (a) radius for roughing: 3.975 mm, rake angle for roughing: 50°, radius for finishing: 4.0 mm, rake angle for finishing: 10°, clearance angle: 12°, interval of edge 40°, (b) radius 4.0 mm, rake angle: 10°, clearance angle: 12°)

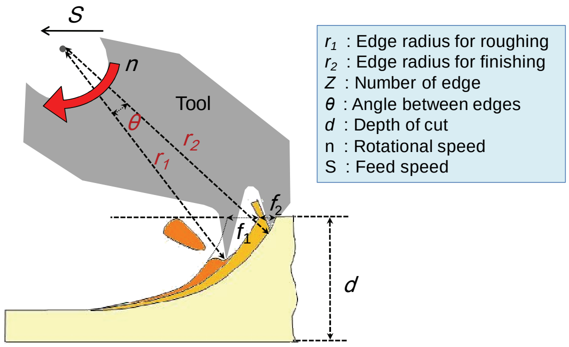


Figure 4: Parameters of cutting tool for bone.

3. Experimental Results

3.1 Bone Specimen

Cortical bone specimens were obtained by cutting slices of the diaphysis of a bovine femur tangential to the bone axis, as shown in Fig. 5. These specimens were extracted from the femur of a 2.5 years-old bovine. In order to prevent residual machining damage to the workpieces and the generation of heat in them, each specimen was cut into 3-mm-thick discs and cooled using a refrigerated saline solution. A saw was fed at a very low speed under cooling using saline, and the surface of the samples was polished underwater using a 1000-grit emery paper #1000 to reduce the influence of surface cracks. The workpieces were frozen at −80 °C after they were prepared; they were thawed by immersing in physiological saline just before the experiments. In the experiments, the cutting tool was fed in tangential direction to bone axis.

3.2 Experimental System

Figure 6 shows an overview of a cutting system. A three-axis force sensor (Kistler 9256) is mounted on a square XY-stage for precision motion control. The workpiece is fixed to a force-sensing table. The machining behavior was observed through a high speed camera (Keyence, VW-6000). Cutting temperature was also measured using a thermography (NEC sanei, TH5100).

Table 1 shows experimental conditions. The milling type was down-cut, and feed per tooth was changed from 50 μm to 350μm assuming practical conditions: tool

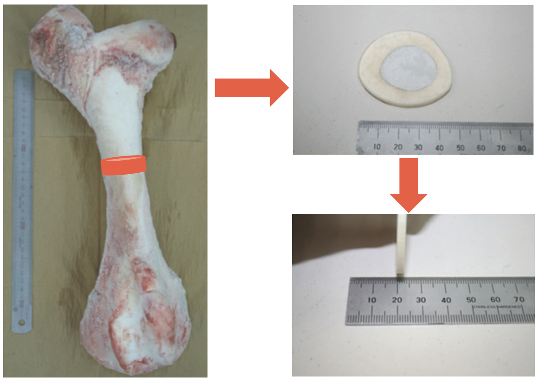


Figure 5: Workpiece of bone

rotation 10000 rpm, tool feed rate 1 m/min to 7 m/min, 2 flutes. In the experiments, the tool rotation was set to 1000 rpm to observe the machining phenomenon.

3.3 Results

Figure 7 shows the observation of the machining phenomenon with the proposal tool. The process was begun with large depth of cut by roughing edge ((a) in Fig.7), and the finish process was started in (b) of Fig.7. The roughing was ended in (c) of Fig.7, and the finishing was completed in (d) of Fig.7. Roughing and finishing were conducted continuously, and the expected result was obtained as shown in Figure 7.

Figure 8 shows the results of the cutting force and the surface roughness. Each plot shows the average or the standard deviation of six examples, and the calculated cutting force means the average of the maximum value in the one process. As the evaluation result of significant difference with t-statistical test, when the feed per tooth

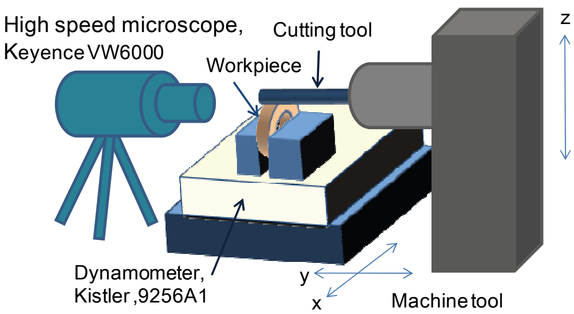


Figure 6: Overview of experimental system.

Table 1 Experimental conditions

Cutting conditions	Cutting type	Down cutting
	Feed per tooth	50, 150, 250, 350 μm
	Rotational speed	1000 rpm
	Axial depth of cut	3 mm
	Radial depth of cut	0.5 mm

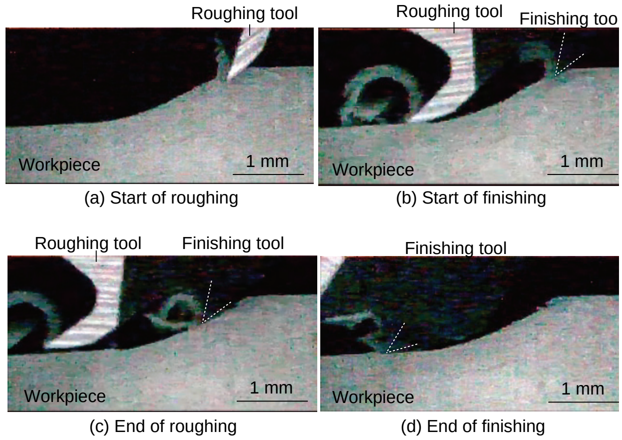


Figure 7: Observation of cutting phenomenon.

is 50 μm, the difference was not confirmed. However, when the feed per tooth is more than 150 μm, the significant difference was confirmed in both the cutting force and the surface roughness.

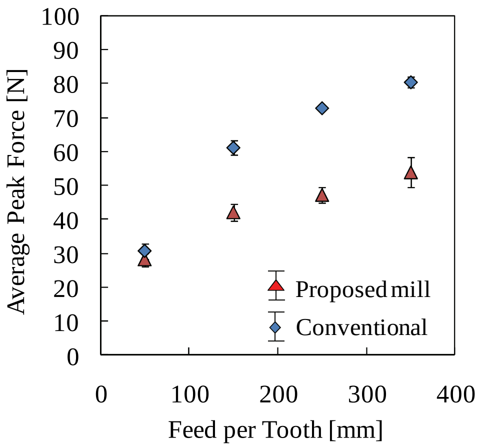
Next, the images from the thermography were analyzed, and the cutting temperature around the tip of edge was acquired. Figure 9 shows the thermal image at the feed per tooth 250 μm. As the result, there is no significant difference in the maximum temperature on the bone surface. However, the heat damage inside workpiece is larger with the conventional method qualitatively. It is expected that the influence of heat could be decreased with the proposed tool in that condition.

4. Discussion

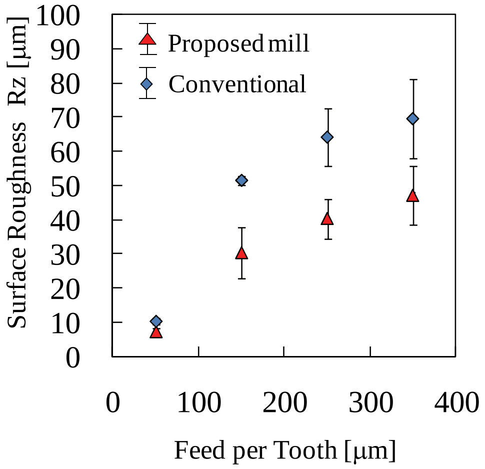
From the experimental results on the cutting force and the surface roughness, when the feed per tooth is more than 150 μm, there was significant difference between the proposed tool and the conventional tool. It is assumed that the process energy was decreased by roughing as observed in Fig.7. The ratio between roughing and finishing is important. The significant difference was confirmed under the range of feed per tooth in these experiments. However, for example, when in the machining with higher efficiency, it is possible that the roughness of surface is degraded and the effect becomes small. The parameters under this condition should be investigated further.

As mentioned, there was no significant difference in the maximum temperature, but the heat damage inside workpiece is smaller qualitatively with the proposed method. With the proposed method, large part is removed by roughing edge, and the rest is finished by finishing edge with the small depth of cut. Therefore, the possibility that the heat is evacuated with the chips becomes larger, and the heat damage to the inside of workpiece was decreased.

It is necessary to conduct the experiments in all cutting direction because the bone has anisotropy. However, the main purposes of this study are to obtain the basic characteristics of the proposed tool and to observe the cutting phenomenon. Therefore, the

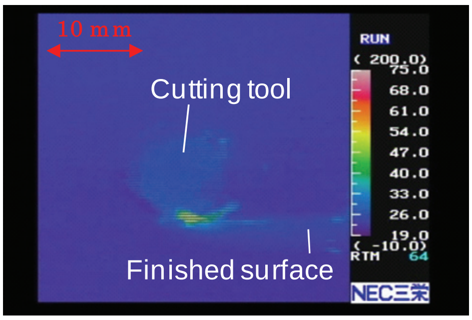


(a) Cutting force

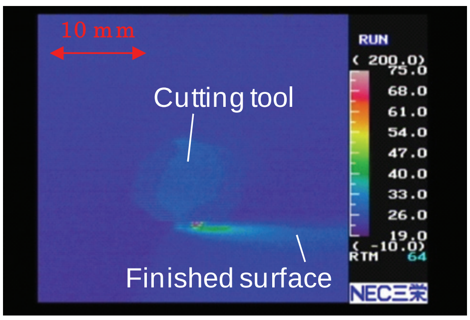


(b) Surface roughness

Figure 8: Experimental results.



(a) Proposed tool



(b) Conventional tool

Figure 9: Thermography image during bone machining (feed per tooth: 250 µm).

cutting direction.

the cutting direction. Some studies have reported the characteristics of bone machining in each direction [5], and the effectiveness of the proposed tool in other directions can be estimated. However, it is necessary to investigate the surface roughness in the across direction because the crack propagates easily in bone axis direction.

Moreover, it is difficult to set the cutting conditions properly because most of bone cutting device is handy type. It is assumed that the clinical conditions are as follows: tool feed rate 1 m/min to 7 m/min, tool rotational speed 10000 rpm, and depth of cut 0.5 mm to 1 mm. These conditions are actually varied during the machining. When the feed speed is decreased, the feed per tooth is also decreased. In that case, the effect by roughing becomes small, and the difference between the proposed and conventional tool also becomes small. The result in feed per tooth 50 µm shows it. Meanwhile, when the feed rate is increased, the feed per tooth is increased. In that case, the effectiveness with the proposed tool was shown in the range of feed per tooth 350µm (tool rotational speed: 10000 rpm, 2 flutes, feed rate 7 m/min), and there is no problem in the condition. However, the case which the feed rate is larger should be investigated.

The proposed tool will be revised by improving the performance of chip evacuation and the layout of cutting edges. Also, the influence of micro crack on the surface will be investigated in the future.

5. Conclusion

The study proposed a cutting tool to realize a method in which the surface is finished precisely with small depth of cut while large part is removed by crack type cutting. It is expected that the method generates the precise surface, and decrease the processing energy, the cutting temperature, and the damage of tissue by the mechanical stress. The effectiveness of the proposed tool was evaluated by some experiments.

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