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The effect of ultrasonic vibration on cutting process of soft composite material

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Development of cutting technology for micro soft composite materials such as cells and biological tissues is highly important in the fields of regenerative medicine, pathology, and drug discovery. However, soft composite materials are not easy to cut because they deform non-linearly when a blade contacts or their cutting characteristics are non-uniform due to their complex compositions. In terms of cutting of such micro soft composite materials, notable phenomena have been reported that cutting performance can be improved by using ultrasonic vibration knife. A typical example of a knife-type tool using ultrasonic vibration is an ultrasonic cutter, but almost ultrasonic cutters are normally designed for crafting or food processing and are not suitable for cutting of such micro soft composite materials. Also, in general, it has been well known that ultrasonic vibration cutting has advantages such as reduction of frictional force between the blade and the material or hemostatic effect. However, few studies have researched the relationship between the vibration behavior of the ultrasonic knife such as how the blade should be vibrated and the cutting performance of micro soft composite materials. Therefore, the purpose of this study was to reveal the mechanism of ultrasonic vibration cutting of micro soft composite materials in viewpoint of vibration behavior. To conduct experiments, an ultrasonic vibration knife assembly which consists of horn, blade and bolt-cramped Langevin-type transducer was designed using finite element analysis and theoretical equation. Then, the knife was fabricated and after that, the vibration of tool top of the ultrasonic knife was measured. From the result, it was confirmed that the amplitude of axial direction was predominantly larger compared to other directions and therefore, it can be said that the tool vibrated in one axis. By changing the direction of the ultrasonic knife blade, pull-cut and push-cut vibration behaviors were given to the ultrasonic vibration knife. Then, biomodelling material was cut by each type of the knife changing the vibration amplitude. From the experiments, the relationship between vibration direction and amplitude and cutting performance of biomodelling material were obtained.

1. Introduction

In the field of regenerative medicine, pathology or drug discovery, improvement of technology of cutting of micro soft composite materials such as cell or biological tissues is important. However, cutting of these materials is difficult. Because they are so soft that they deform non-linearly when blade is contacting to them. Also, because they are consisted of complex composition, their cutting characteristics are non-uniform.

Regarding such materials, notable phenomena have been observed that knife with ultrasonic vibration enables to cut them or to improve cutting performance. Ultrasonic cutter is famous for knife-type ultrasonic tool. However, it is usually designed for crafting or food cutting and not suitable for cutting of such micro soft composite materials. Also, in general, ultrasonic vibration cutting has advantages such as reduction of frictional force between blade and work [1] or hemostatic effect. However, few studies have examined the relationship between the vibration behavior of the blade and the cutting performance.

Therefore, purpose of this study is to clarify the mechanism of cutting of micro soft composite materials from the viewpoint of vibration behavior of tool blade. In this report, first, characteristics of ultrasonic knife designed and made were explained. Second, result of experiment using the made ultrasonic knife and biomodelling test piece was explained. In the experiment, the effects of vibration direction and amplitude of the blade on cutting performance were examined.

2. Ultrasonic tool

2.1 Designing and making tool

To performing experiment, ultrasonic tool was designed and made. The tool is shown in Fig.1. The tool is composed of 40kHz bolt-clamped Langevin-type transducer, ultrasonic horn, and blade.

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The horn was made of Aluminum alloy and its dimension was determined from theoretical equation [2] and FE software. Also, blade used in this research was cut out from 99224 blade of FEATHER Safety Razor Co., Ltd to 6mm × 15mm size and fixed on the horn top with adhesive. Result of characteristic mode analysis of the tool was shown in Fig.2. From the result, it was found that the tool had characteristic mode which vibrates in axial direction at 41.513kHz.

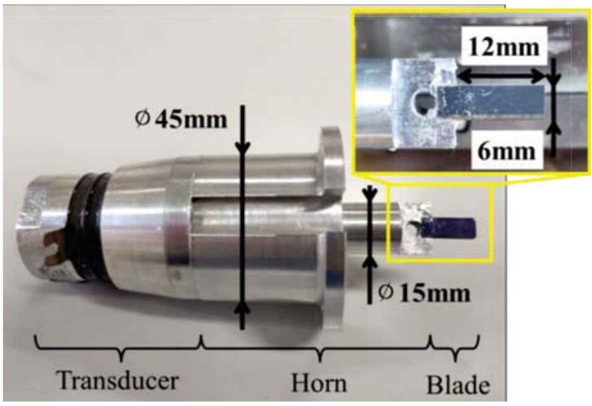


Fig.1 Designed and made ultrasonic tool

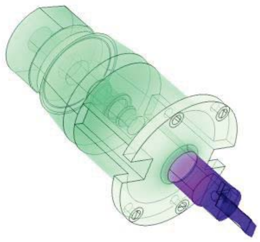


Fig.2 Characteristic mode of the tool at 41.513kHz

2.2 Performance evaluation of made tool

To confirm vibration property of the tool, frequency response in axial direction was investigated. Using Laser doppler vibrometer, axial vibration of top of the blade edge was measured varying frequency ranging from 35kHz to 50kHz. Voltage input to piezoelectric element was kept constant at 60Vpp. The result is shown in Fig.3. It was found that the tool had maximum amplitude in axial direction at 41.35kHz. The difference between analysis and experiment results may be caused by material property, restraint condition on FE analysis, and unevenness of the adhesive. Also, Table.1 shows the amplitude of each direction when increasing the applied voltage in 50Vpp steps. These result shows that the tool has vibrational mode that axial vibration is predominantly larger than other directions around 41kHz. Here, Tsuda et al. establishes that more than 30μm amplitude of axial direction improved cutting performance of pig meat at 20kHz. [3] Assuming that axial vibration would be sin wave and maximum cutting speed, i.e., product of amplitude and frequency is a dominant factor, it was considered that the made tool also should achieve Tsuda's value, which is $20\text{kHz} \times 30\mu m = 600\mu m/s$. The made tool should have more than around 14.5μm of axial amplitude at 41.35kHz and actually it can output maximum about 13.5μm. It was considered that output performance would be sufficient.

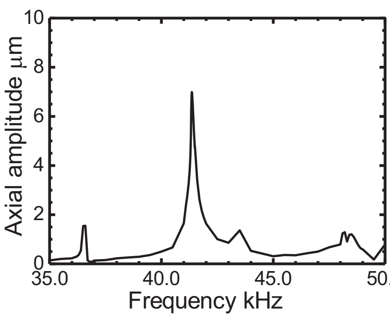


Fig.3 Frequency response in axial direction at voltage 60Vpp

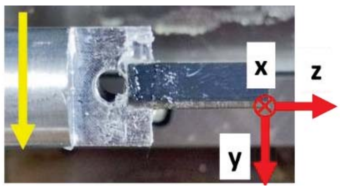
Table.1 Amplitude of each direction at 41.35kHz

Input voltage Vpp	Amplitude μm		
	Axial	Side	Vertical
50	4.588	0.241	0.755
100	11.887	0.403	1.141
150	13.163	0.546	1.434
200	13.691	0.831	1.875

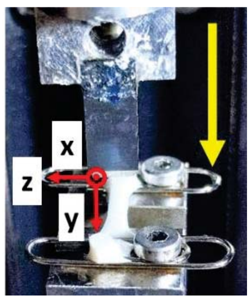
3. Cutting experiment

3.1 Procedure

To examine the effect of amplitude and vibration direction on cutting performance, cutting experiment were performed. As shown in Fig.4, by using two types of blades which have the same size but different position of blade edge, vibration direction applied to blade could be change easily. Cutting tool shown in Fig4(a) was named Knife-type and Fig.4(b) was named guillotine-type. Knife-type enables pull-cut and guillotine-type enables push-cut. There was a



(a)Knife-type



(b)Guillotine-type

Fig.4 Two types of cutting methods

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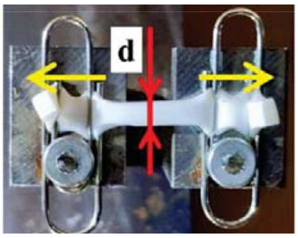
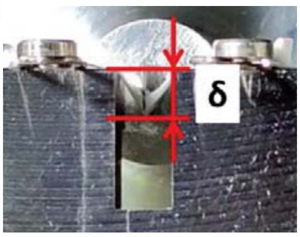
possibility that the resonance frequency could change due to installation or removal of the blade. Then, applied vibration frequency was determined by testing response frequency in axial direction before performing each experiment. After that, by changing input voltage, 2, 4, 6, 8, 10, 12μm of amplitude in z-axis for knife-type and in y-axis for guillotine-type were applied to the blade. Including 0μm of amplitude, which means no ultrasonic vibration was applied, cutting experiment was performed under seven conditions of axial amplitude for each experiment. Cutting experiment was performed three times for each condition. Also, using two laser displacement sensors, phase differences in z-x and z-y plane were obtained by measuring vibration in two axes simultaneously.

Two types of biomodelling test pieces were used for experiments. One of them had 3mm width and 2mm thickness and the other had 4.5mm width and 1mm thickness. Both pieces consisted of the same composition and the hardness was about 35 with ASKER durometer Type CS. The test piece was fixed under tension as shown in Fig.5(a) and width d of the center was set to 2.5mm for the 2mm thickness test piece and 3.6mm for 1mm thickness test piece. Then, the blade was



(a)View from above



(b)View from the front

Fig.5 Fixed test piece

Table.2 Experiment conditions and vibration amplitude of each direction

Experiment No.	Cutting type	Thickness of test piece	Applied frequency kHz
1	Knife-type	2mm	41.21
2	Knife-type	2mm	41.21
3	Guillotine-type	2mm	41.21
4	Knife-type	1mm	41.35
5	Guillotine-type	1mm	41.31

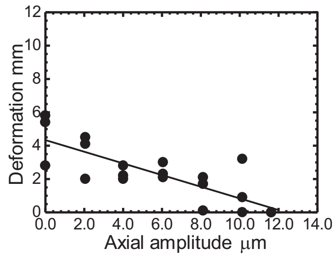
approached to the piece quasi-statically and the deformation δ as shown in Fig.5(b) was measured until the piece was completely cut. All experiment conditions are summarized in Table.2.

3.2 Result of experiment

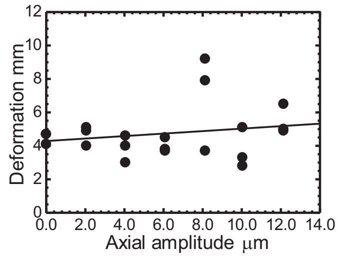
Table.3 shows the measurement result of the amplitudes in experiment No.2 as an example. The amplitude in z-axis direction could be adjusted to 2, 4, 6, 8, 10, 12μm. Also, the amplitudes in x-axis and y-axis directions were still smaller than axial amplitude. Fig.6 shows results of all cutting experiments. Horizontal axis represents the axial vibration amplitude of the blade edge and vertical axis represents the value of deformation of test piece to complete cutting. ● represents success of cutting and × mark represents cutting was not completed due to the predetermined limit which came from the blade length 12mm. This limitation of deformation depth was only for guillotine-type blade. From the results, in general, cutting performance appears to be improved when ultrasonic vibration was applied parallel to the blade rather than perpendicular. For example, as shown in Fig.6(a), cutting performance was highly improved according to increase of axial amplitude in experiment No.1. Similarly, when axial amplitude is more than 10μm, cutting performance was improved in experiment No.5 as shown in Fig.6(d). However, for guillotine-type, vibration perpendicular to the blade

Table.3 amplitude of each direction on experiment No.2

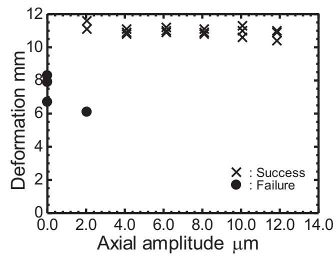
Amplitude μm		
x(side)	y(vertical)	z(axial)
0.11	0.16	2.05
0.18	0.36	4.05
0.24	0.59	6.08
0.31	0.69	8.13
0.84	0.84	10.04
1.02	1.07	12.14



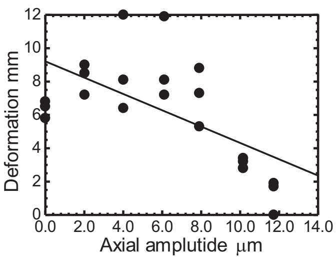
(a)No.1(2mm, knife-type)



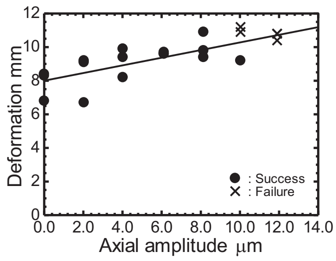
(b)No.2(2mm, knife-type)



(c)No.3(2mm, guillotine-type)



(d)No.4(1mm, knife-type)



(e)No.5(1mm, guillotine-type)

Fig.6 Experiment results

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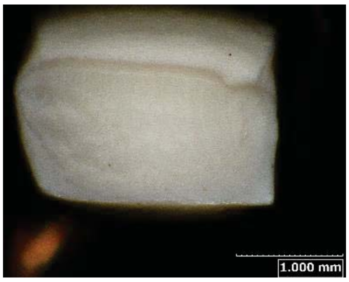
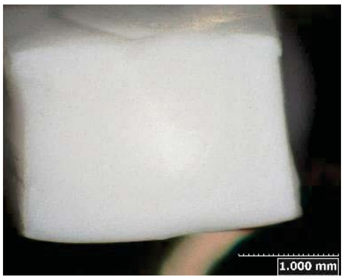
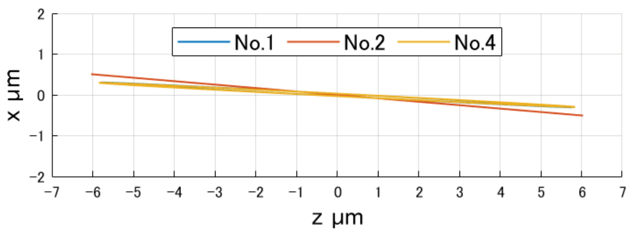


(a)Axial amplitude: 0µm (without ultrasonic vibration)

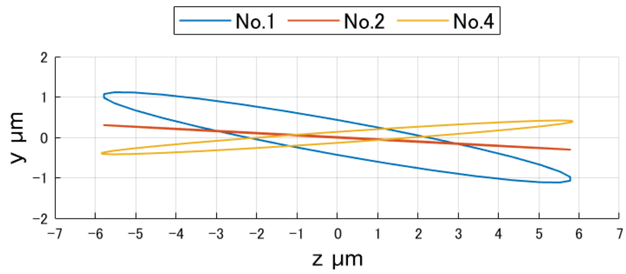


(b)Axial amplitude: 12µm (with ultrasonic vibration)

Fig.7 Cut surface of 2mm thickness test pieces on experiment No.1



(a)z-x plane



(b) z-y plane

Fig.8 Vibration trajectory of blade top in experiment No.1 and No.2

edge did not affect on cutting performance as shown in Fig.6(c) and (e).

Fig.7 shows cut surface of 2mm thickness pieces on experiment No.1 with 0 and 12µm amplitude. The surface cut with ultrasonic vibration is smoother than without ultrasonic vibration. Also, upper edge of the surface shown in Fig.7(a) is deformed and rounded due to compressive stress given from blade when the test piece was being cut, while that of the surface shown in Fig.7(b) is square. From these figures, it was found that test piece was cut without being collapsed due to ultrasonic vibration applied parallel to the blade. From the results written above, that ultrasonic vibration applied parallel to the blade may have a positive effect on cutting of micro soft composite materials. On the other hand, there is no effect in experiment No.2 despite under the same condition as No.1. To clarify this point, vibration trajectories of top of the blade edge were obtained from measurement of amplitude and phase. Fig.8 shows the vibration trajectory in experiment No.1, No.2, and No.5. Although all trajectories in z-x plane are almost the same, a different point can be observed of the three trajectories in z-y plane. The trajectories in experiment No.1 and No.4 are elliptical while the trajectory in experiment No.2 is linear. In the field of turning or milling process, elliptical vibration is well known for giving some effective benefits, for example, reduction of cutting resistance or chip thickness or cutting of difficult-to-machine materials.[3],[5] However, elliptical vibration cutting in this research is different from general elliptical vibration machining whether elliptical vibration is in the plane of the blade or in a plane orthogonal to the blade. Therefore, it is necessary to conduct detailed research about the relationship between elliptical vibration and improvement of cutting of micro soft composite materials as a future task.

4. Conclusions

In this research, to clarify the effect of the ultrasonic vibration behavior of the blade on cutting performance of micro soft composite materials, the relationship between vibration direction and amplitude of the blade on cutting performance were examined. Ultrasonic tool was designed and made. And using the tool, cutting experiment was performed. As a result, following items were obtained.

1. Ultrasonic vibration applied parallel to blade may be more effective than perpendicular.
2. For improving cutting performance, there is a possibility that two important vibration characteristics is important, i.e., amplitude and elliptical vibration.

In future project, elliptical vibration will be applied to the blade edge and the effect on cutting performance of micro soft composite materials will be examined. Also, using FE software or by measuring cutting force, cutting mechanism will be clarified in more detail.

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