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Control of chip flow with guide grooves for continuous chip disposal and chip-pulling turning

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ABSTRACT

This paper presents a new chip control method with guide grooves formed on the rake face to realize continuous chip disposal and chip-pulling turning. Chips are conventionally broken using chip breakers during turning operations for disposal. However, chips of highly ductile materials or thin chips generated in finishing can not be broken easily. In order to prevent the chips from jamming up, the authors propose to continuously guide the chips away from the cutting point. Special tool tips were developed and tested for guiding the chip. Chip controllability and mechanics of the chip-guided cutting are discussed in the present research.

1. Introduction

Turning is an efficient material removal process, i.e. a large volume of chips is generated from the cutting point. In order to prevent the chips from jamming up, chips are assisted to curl up and broken into pieces using chip breakers in the current practice. However, chips of highly ductile materials or thin chips generated in finishing cannot be broken easily. For example, various drive-train components of vehicles such as shafts and deep drawn parts are mass-produced from ductile steel and aluminum where the chip often jams up during finish cutting. The chip jam causes practical problems such as tool breakage and deterioration of the surface quality [1].

In order to solve this practical problem of chip jam, a new concept of continuous chip disposal is proposed in this research. The concept is illustrated in Fig. 1. The chip is controlled not to curl up but guided into a guide tunnel. This concept can also be combined easily with chip-pulling cutting. It was known that the cutting process is improved significantly by pulling the chip, e.g. the overall cutting energy including the pulling energy could be reduced by half [2]. Contrary to this great advantage, chip-pulling cutting technology has not been progressed for many years except elliptical vibration cutting [3,4], which can be understood as a special type of the chip-pulling cutting and has been successfully applied in practice in low-speed ultraprecision machining. Main reason for this limited progress may be lack of suitable chip control method to guide the chip to a pulling device.

Therefore, a new chip control method is developed in this research as a basic technology to realize continuous chip-pulling cutting and chip disposal. Guide grooves are formed on the rake face to suppress the chip curl and to control the chip flow direction. In addition, a guide tunnel is mounted on the rake face aligned with the chip flow direction to navigate the chip into a chip disposer or a chip-pulling device as shown in Fig. 1. Using the developed tools with guide grooves and the guide tunnel, it is confirmed that the chip can be guided successfully over a wide range of cutting conditions to the desired direction where it can be disposed or pulled. Mechanics of the chip-guided cutting are also discussed on the basis of measured cutting forces.

2. Development of chip control technology for continuous chip disposal

2.1. Suppression of chip curl and control of chip flow direction with guide grooves

Firstly, cutting tests were conducted at ordinary cutting conditions to observe ordinary chip formation. Cold rolled steel (JIS: SPCC) was used as the workpiece material, and the cutting was performed at conditions given in Table 1. Fig. 2(a) shows the chip flow observed when using an ordinary flat rake face tool. As shown in Fig. 2, the chip is mainly curled sideward, and up-curl was not significant.

It is considered that the side-curl is mainly caused by the side-flow of the workpiece material [5]. The side-curl mechanism is illustrated in Fig. 2(b). The material can flow sideward in the shear zone on the free uncut surface side, while it cannot easily flow sideward on the cut surface side. This reduces the chip flow speed on the free surface side and generates the side-curl. On the other hand, the chip flow direction changes widely with cutting conditions and the tool geometry. Colwell's rule [6] approximates the chip flow direction to be normal to the chord joining the extreme points of the engaged cutting edge (See Fig. 2(b)). Hence, in order to realize continuous chip disposal and the chip-pulling cutting, the chip needs to be controlled not to curl but be guided and flow in the desired direction.

A new chip control method is proposed in this research, which utilizes guide grooves formed on the rake face to cope with those bottlenecks and achieve continuous chip-pulling cutting. Fig. 3 shows the developed cutting tool where guide grooves were

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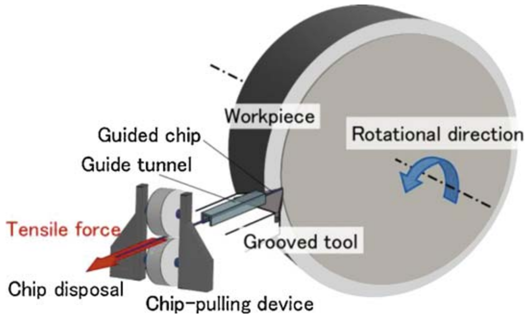


Fig. 1. Concept of continuous chip disposal, which can be combined with chip-pulling cutting.

Table 1
Experimental conditions.

Workpiece	Material	Cold rolled steel (JIS: SPCC)
	Diameter	150 mm
Tool	Material	Sintered tungsten carbide
	Rake/relief angle	0/11°
	Nose radius	0.8 mm
Process		Face turning
Cutting conditions	Rotational speed	561 rpm
	Cutting speed	238–264 m/min
	Depth of cut	0.4 mm
	Feed rate	0.12 mm/rev

machined using EDM (Electrical Discharge Machining) on the rake face. The turning process with the grooved tool is illustrated schematically in Fig. 4(a). The chip is formed at the grooved tool tip, and it flows through the guides on the rake face. The cutting pressure forges grooves on the cut chip in the proposed method. As a result, the chip is constrained to flow through the guide grooves. Since the entire region of the engaged rake face is machined with the grooves, the side-flow of the material is restricted, which also eliminates the side-curl. Thus, the cut chip can be guided straightly on the rake face.

Fig. 4(b) shows the chip flow with the grooved tool. The experimental conditions are identical with the above ones given in Table 1. The only difference from Fig. 2(a) is that the tool used in Fig. 4(b) has the proposed guide grooves on the rake face. By comparing Figs. 2 and 4, it is clear that the guide grooves can successfully suppress the side-curl and control the chip flow direction.

2.2. Chip navigation with guide grooves and guide tunnel

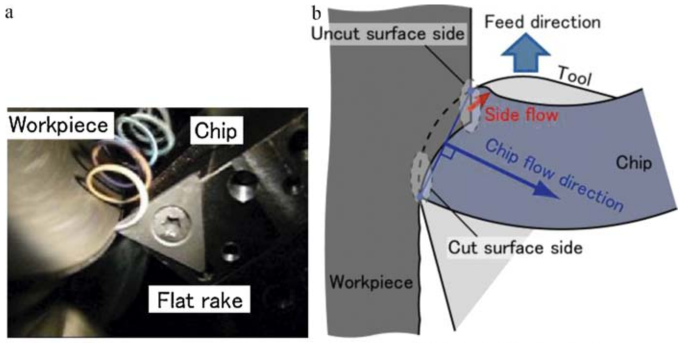
A guide tunnel, shown in Fig. 5, was developed to navigate the chip to a desired position for chip disposal. The tunnel consists of four parts with a total length of 125 mm. The entrance of the tunnel is 4 mm away from the tool tip, and this first part of the tunnel is made of sintered tungsten carbide. The following three parts are made of steel except the observation window of glass and polycarbonate. Sizes of the four parts of the tunnel are gradually increased so that the chip can flow smoothly.

In order to test the effectiveness of the guide tunnel, a chip navigation test was conducted using the guide-grooved tool at the above cutting conditions. As shown in Fig. 6, the tool is inclined from the spindle axis. This inclination is defined as the chip guide angle in this manuscript, and its effect is discussed in the next section. In this experiment, the chip guide angle was set to 45°. Fig. 7 shows that the chip can be navigated successfully through the tunnel for continuous chip disposal.

3. Chip controllability by the developed chip navigation method

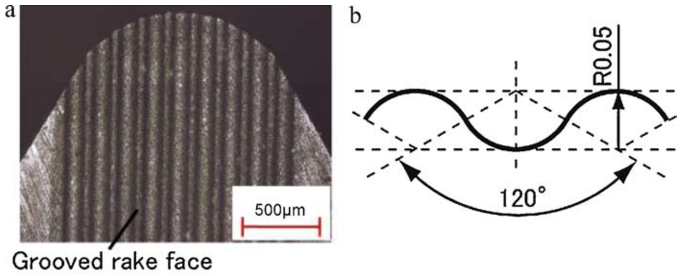
In order to evaluate chip controllability by the developed chip navigation method, machining experiments were conducted at various cutting conditions using tools with and without the guide grooves on the rake face. The depth of cut and feed rate were varied incrementally from 0.2 to 0.8 mm and from 0.06 to 0.24 mm/rev respectively. The chip guide angle was also increased from 0° to 45°. The navigation experiments were conducted twice at each set of conditions, and the chip controllability is evaluated by observing successful navigation of the cut chip through the guide tunnel. Table 2 summarizes cutting conditions and results of the chip navigation at different chip guide angles. The chip flow angle, on the other hand, was measured on the ordinary flat rake face tool, and given as a reference here.

The chip guide angle is an important parameter on successful chip navigation, whose effect is shown in Table 2. The chip navigation succeeded at every chip guide angle at a depth of cut of 0.2 mm and a



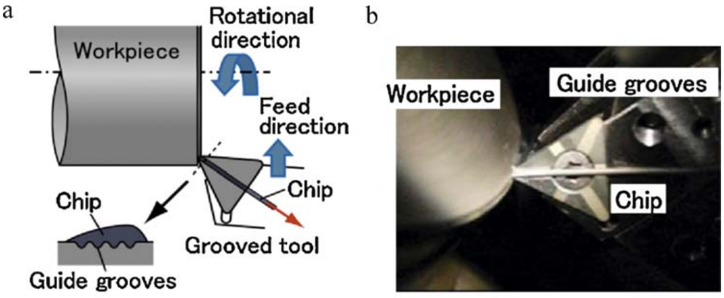
Photograph of chip flow Mechanism of side-curl of chip

Fig. 2. Chip flow with flat rake face.



Microphotograph Cross section

Fig. 3. Developed tool with guide grooves.



Turning with guide-grooved tool

Chip flow with guide-grooved tool

Fig. 4. Suppression of the side curl and control of flow direction with guide grooves.

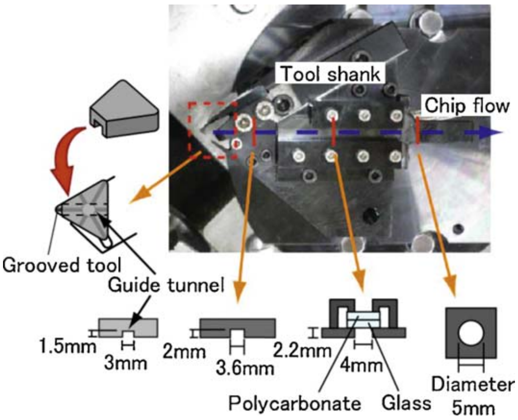


Fig. 5. Guide tunnel with observation window.

feed rate of 0.06 mm/rev. Hence, using the guide-grooved tool the original chip flow angle of 23.9° can be varied with the chip guide angle. As the depth of cut and the feed rate increase, the original chip flow angle differs from small chip guide angles, and the chip navigation tends to fail. The navigation was especially difficult at a feed rate of 0.24 mm/rev since the chip thickness becomes larger and cannot pass through the entrance of the guide tunnel.

4. Mechanics of the chip-guided cutting

An insight into the mechanics of the chip-guided cutting is given in this section. The principal, friction and chip guiding forces, as shown in Fig. 6, were measured with a dynamometer fixed under the cutting tool in the above navigation experiments. The forces and the associated angles are plotted in Fig. 8. Marks plotted in Fig. 8 indicate their corresponding cutting conditions and they are color-coded with regard to the 4 different sets of depth of cut and feed rate, which are given on the upper table in Fig. 8. As shown in Fig. 8, the principal and friction forces are roughly constant at various chip guide angles at each set of depth of cut and feed rate. They are also roughly the same as the forces measured with the flat rake face tool. In the proposed method, the chip flow is restricted into the chip guide direction by the chip guiding force N', which acts on the side surfaces of the grooves. This chip guiding force N' increases linearly as the chip guide angle is increased from the original chip flow angle. This is simply because more force is needed to guide the chip into the desired direction. The friction angle, on the other hand, was identified as the angle between the resultant force R and its component on the normal plane to the chip flow. The friction angle is roughly constant. Force angle on the rake face was defined as an angle between the spindle axis and the resultant force projected on the rake face as shown in Fig. 6. The force angle is approximately constant at every set of depth of cut and feed rate. To be exact, it slightly decreases with an increase in the chip guide angle. The mechanics can be assumed as follows.

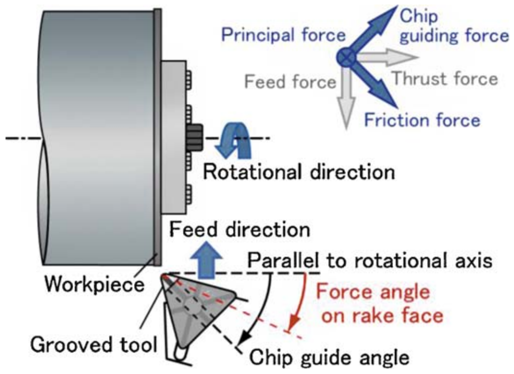


Fig. 6. Definition of angles and forces acting on the tool.

Fig. 9 illustrates the forces acting on the chip during the ordinary cutting and the chip-guided cutting process with the guide grooves. Note that Fig. 8 shows their reaction forces acting on the tool. The ordinary cutting without the grooves is shown by the broken lines. The friction force $\vec{f}$ acts on the chip in the opposite direction to the chip flow velocity, and the principal force $\vec{F}_p$ acts perpendicularly to the rake face. Note that the rake face is perpendicular to the cutting velocity in this study for simplicity. Thus, all the velocities and forces including the resultant force $\vec{R}$ and its projection onto the shear plane $\vec{F}_s$ lie on the same plane. On the other hand, the proposed process with the guide grooves is shown by the solid lines where the chip flow is changed by the guide grooves, and the friction force $\vec{f}'$ is aligned with the guide direction. This difference in the friction force $\vec{f}' - \vec{f}$ is roughly canceled by the chip guiding force $\vec{N}'$. This is why the force angle is approximately constant. To be exact, the guiding force slightly over-cancels the change in the friction, as shown in Fig. 9. This is because the resultant force $\vec{R}'$ needs to produce the shear force $\vec{F}_s'$ as its component in the shear direction, which lies on the plane including the guided chip flow and cutting directions.

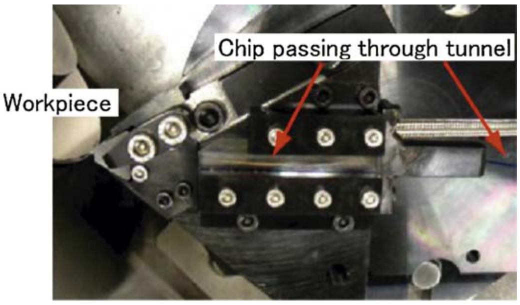


Fig. 7. Chip navigated with grooves and tunnel in face turning.

Table 2
Results of chip navigation with guide grooves and tunnel.

Depth of cut (mm)	Feed rate (mm/rev)	Chip flow angle with flat rake (°)	Chip guide angle (°)			
			0	15	30	45
0.2	0.08	23.9	2	2	2	2
0.4	0.12	31.4	0	1	2	2
0.6	0.18	40.2	–	1	1	2
0.8	0.24	53.9	–	–	0	2

0, 1, 2: number of successful navigations out of two trials; –: no data.

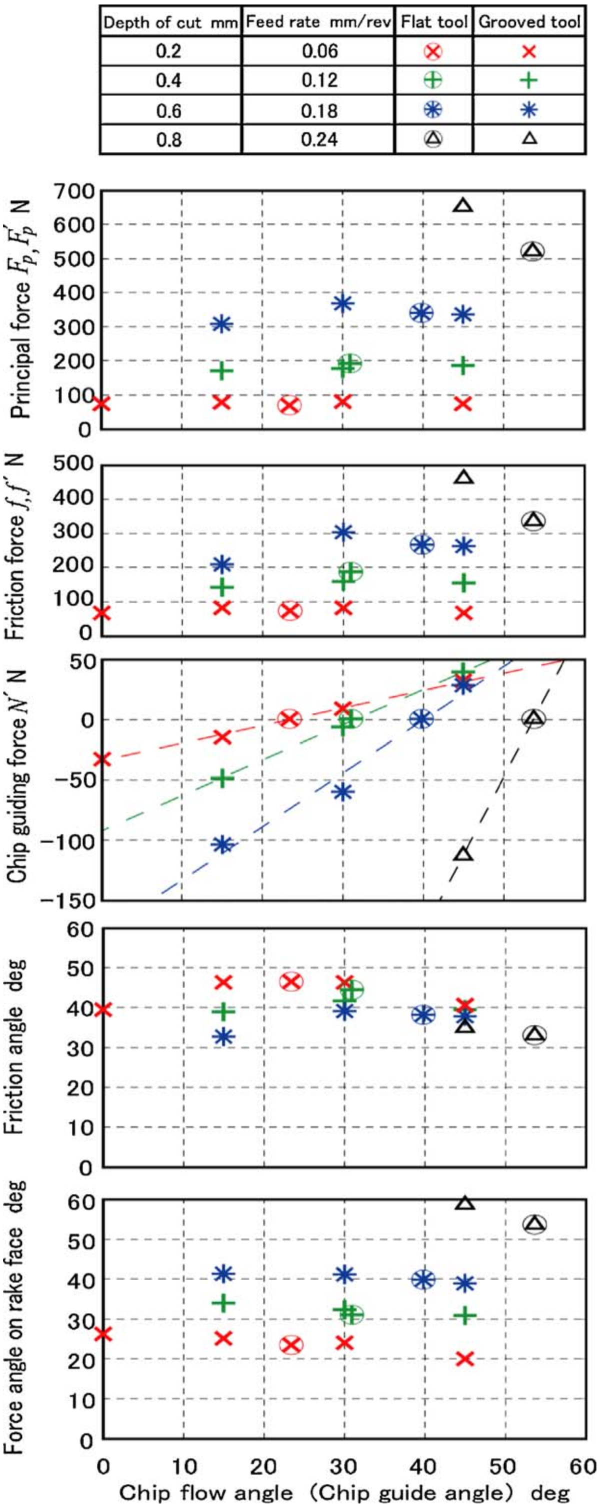


Fig. 8. Measured forces and angles with and without guide grooves.

5. Manual chip-pulling test

The chip-pulling turning was conducted as a trial in order to confirm its effectiveness. The rolled steel was turned with the guide grooves at a guide angle of 30°, and the chip was caught and pulled manually with pliers. The cutting conditions are the same as the above ones shown in Table 1 except that the rotational speed was reduced for safety to 317 min^{-1}, which corresponds to 146 m/min in average.

The result of the pulling effect is shown in Fig. 10. It demonstrates that the cutting forces can be reduced to about half with the chip-pulling. Thickness of the chip t was also measured in three regions shown by gray lines and the average values are also shown in the figure. The original thickness 0.69 mm was reduced to 0.55 mm with mild chip-pulling and then to 0.37 mm with strong chip-pulling. This significant reduction of the chip thickness suggests that the friction force acting on the chip is cancelled by the chip-pulling force, and it leads to significant reduction of the shear area, cutting forces and the cutting energy.

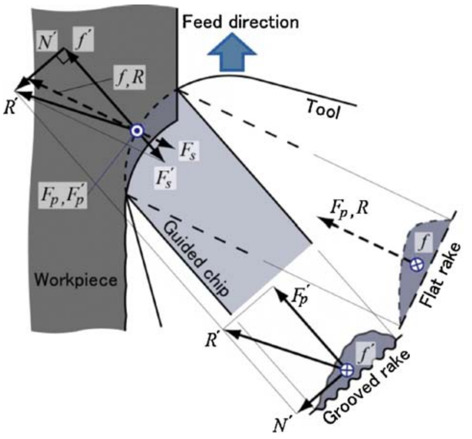


Fig. 9. Forces acting on the chip with and without guide grooves.

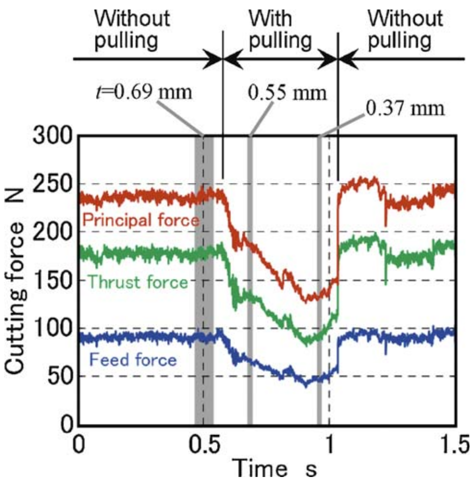


Fig. 10. Reduction in the cutting forces with manual chip-pulling.

6. Conclusion

A new chip control method with guide grooves and guide tunnel was developed and verified to realize continuous chip disposal as well as chip-pulling cutting. It was confirmed that the chip can be navigated through the guide tunnel over a wide range of cutting conditions. Magnitude and direction of the cutting forces are not very different from those measured with the flat rake face tool even when the chip flow direction is changed considerably with the guide grooves. The guided chip was pulled manually, and the result demonstrated that the chip thickness and the cutting force can be reduced by about half.

It is expected that continuous chip disposal and chip-pulling cutting will be realized with the proposed chip control method to avoid the chip jam and improve the cutting performance significantly.

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