High-Efficiency Cutting of Super-Heat-Resistant Alloy

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Inconel 718, a super-heat-resisting alloy, is difficult to cut, increasing the need for more efficient cutting. Tool wear in commonly used coated cemented carbide tools is identified clearly based on observations during cutting experiments. Tool life in interrupted cutting is shorter than during continuous cutting because the built-up edge is removed, causing the coating film to flake when the tool parts from the workpiece during interrupted cutting. Cutting that gradually reducing undeformed chip thickness at cutting end prevents the separation of built-up edges and reduces tool wear during interrupted cutting.

1. Introduction

Inconel 718, a supper-heat-resistant alloy used in parts of gas turbines and airplane engines, is known as a material that is difficult to cut. Under the same cutting conditions, tool wear progresses at a noticeably quicker pace than when cutting metals such as carbon steel, consequently, at the present time the cutting speed is reduced during machining work. It is difficult to reduce the cost of machining of the aforementioned parts. For high-efficiency cutting of such difficult-to machine materials, it is necessary to improve tool materials and machining methods to reduce tool wear.

This study was made to clarify the tool wear mechanism for cutting of Inconel 718 super-heat resistant alloy using coated cemented carbide tools which are generally used(1). This paper shows that the tool wear mechanisms in continuous and interrupted cutting are different as found through observation of tool wear during cutting experiments. It is shown that the wear mechanism is deferent depending on the cutting speed in continuous cutting and methods to restrain wear in interrupted cutting are studied.

2. Tool wear mechanisms in cutting super-heat-resistant alloy

2.1 Experimental method

Using a MALC10 CNC lathe made by Mitsubishi Heavy Industries, Ltd. (MHI), peripheral turning was performed using a round bar. There are two major types of cutting, continuous cutting, which was represented by turning, and interrupted cutting, represented by milling. During continuous cutting, the tool temperature and stress are nearly at a steady state, while during interrupted cutting, they are changing because of repeated cutting and slipping. Such differences in cutting forms also affect the tool wear, and with interrupted cutting, the tool life of a coated cemented carbide tool is 1/10 or less than with continuous cutting. Therefore, so as to clarify the differences in the wear mechanisms of both forms of cutting, interrupted cutting was performed by peripheral turning of a round bar grooved in the longitudinal direction. Cutting conditions other than the workpiece shape were the same as those of continuous cutting. The tool used was a square throw-away chip of commercial coated cemented carbide (P20, TiN, TiC multilayered coating).

The cutting temperature was measured by the tool-workpiece thermocouple method(2). Furthermore a scanning electron microscope (SEM) was used for observation of the tool wear surface and a electron probe microanalyzer (EPMA) and an Auger electron spectroscopic analyzer (Auger) were used for element analysis of the tool wear surface.

The experimental conditions were as shown in **Table 1**. And the chemical components of Inconel 718 used in the experiment are shown in **Table 2**.

2.2 Tool wear during continuous cutting

First, to observe the wear process of a coated cemented carbide tool during continuous cutting, turning was performed using a round bar of Inconel 718.

Table 1 Experimental conditions

Tool	Material Shape	Coated cemented carbide (P 20, TiN-TiC coating) 5, 5, 6, 6, 45, 45, 0.8
Workpiece	Material Shape Hardness	Inconel 718 φ100×1200 mm HB 415
Cutting conditions	Cutting speed Depth of cut Feed rate	30, 100 m/min 0.25 mm 0.2 mm/rev.
Cutting fluid		Dry

Table 2 Chemical composition of Inconel 718

Chemical composition	Ni	Cr	Fe	Co	Mo	C	Mn	Si	Al	Ti	Nb
Weight %	52.4	18.6	18.9	0.13	3.19	0.04	0.07	0.06	0.65	0.86	5.1

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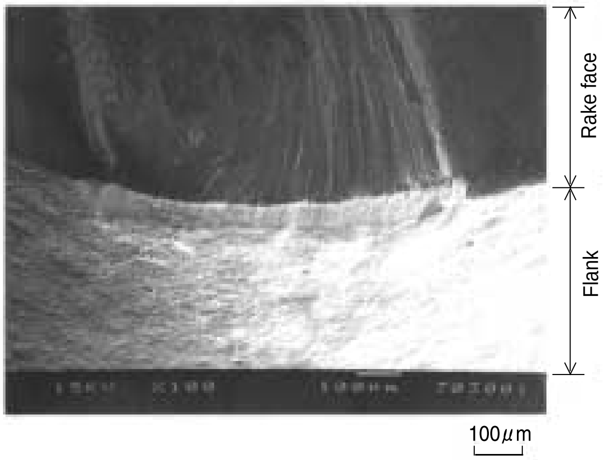


Fig. 1 Tool after cutting 30 m (cutting speed: 30 m/min)
The photograph shows the diagonal direction and from the upper direction. Inconel 718 is adhered to the rake face.

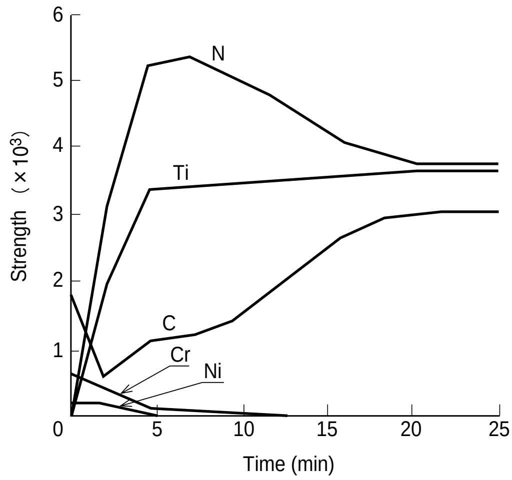


Fig. 3 Element analysis of flank wear area
The results of element analysis using an Auger in the depth direction are shown. First, Ni and Co and after wards hot Ti and N are detected.

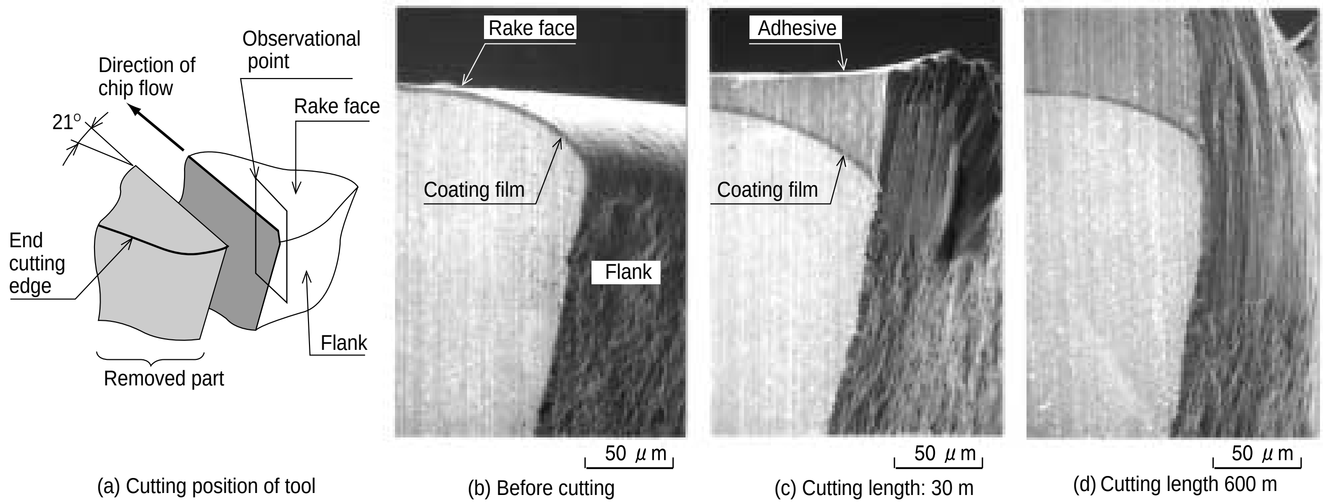


Fig. 2 Observation of the tool section
The coating film on the rake face has no wear even after cutting 600 m.

The cutting speed was a standard 30 m/min.

Fig. 1 shows the result of observation by SEM of the tool after Inconel 718 was cut to a length of 30 meters. It was found that the adhesive of the Inconel 718 workpiece was deposited on the rake face of the tool.

Next, in order to investigate the wear conditions of the coating film in detail, tool sections were observed, **Fig. 2** shows the position of the sections and direction of observation and the results of the observation by SEM of the tools before and after cutting (cutting distance was 30 meters and 600 meters). The observation section of the tool was inclined by 21° from the end cutting edge so that it would be parallel to the direction of chip flow and ground out to the center of the width of contact with chips. The tool cross section was created by the above method. In Fig. 2 (b)−(d) of SEM photographs, approximately 5 μm of the surrounding thickness of the tool section shows the coating film after cutting adhesive was observed on the rake face of any tool. Furthermore when the tool section was surface-analyzed with the EPMA, it was verified that the adhesive on the rake faces was Inconel 718 and in the same figure, the dark area around the cemented carbide base metal was the coating film. The adhesive was deposited on the coating film and even after cutting 600 meters, the coating film on the tool rake face exists without wear. On the other hand, it was found that the wear of the flank progresses to cemented carbide base metal after 600 meters of cutting.

From the above, it is believed that under these cutting conditions, immediately after cutting is started, the workpiece adheres to the rake face and because this adhesive becomes a stable built-up edge and cuts so as to protect the rake face, wear of the rake face is almost not found and only the flank wears. It was verified by observing the surface of the workpiece and the chips that the built-up edge is not released.

Next, in order to examine the wear mechanism of

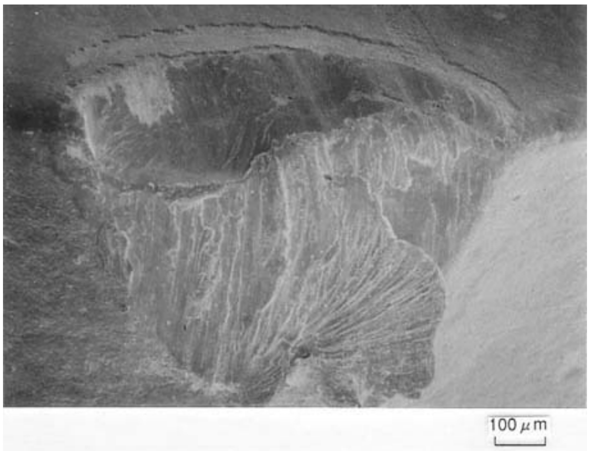


Fig. 4 Tool after cutting 69 m (cutting speed: 100 m/min)
The rake face and flank are greatly worn at a cutting length of 69 m and further cutting becomes impossible.

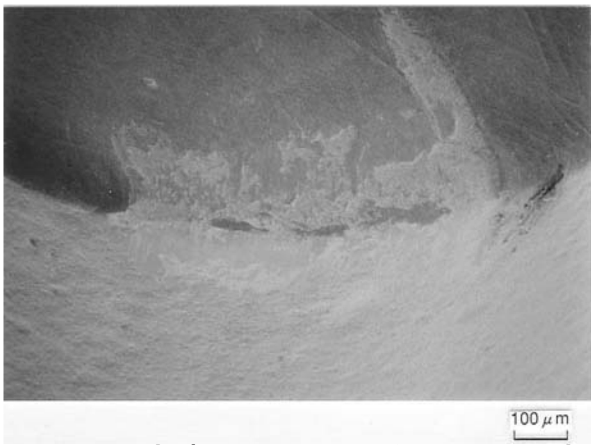


Fig. 5 Tool after cutting 5 m (in interrupted cutting)
Adhesive on the rake face is not removed.

the flank, Auger was used to perform element analysis in the depth direction on the worm part of the flank for the tool after 600 meters of cutting. **Fig. 3** shows the analytic results. The horizontal axis of the detection time corresponds to the depth from the surface. Also the vertical axis shows the density of the element. Firstly Ni and Cr which are composition elements of Inconel 718 are detected, thereafter Ti and N which are composition elements of the coating film, are detected. It is found by the above that Inconel 718 adheres to the surface of the wear area of the flank. It is believed that when cutting Inconel 718, adhesive wear progresses due to repeated adhesion of the workpiece and the coating film and releasing of the tool material on the flank during cutting.

The tool wear was observed at the standard cutting speed of 30 m/min and when cutting is at a high speed, it is known that the tool is instantaneously worn. Therefore, it was determined that the wear behavior should be examined during high speed cutting. **Fig. 4** shows the tool wear when Inconel 718 is cut for 69 meters at a cutting speed of 100 m/min. Wear of both the rake face and flank had greatly progressed by a cutting distance of 69 meters and further cutting was not possible. Also cutting was performed several times under the same conditions, but the same tendency was obtained in all cases.

The cutting temperature was measured and found to be 990 K at a cutting speed of 30 m/min and 1 320 K at a cutting speed of 100 m/min. The tensile strength of Inconel 718 rapidly decreases at high temperatures from about 970 K and at 1 070 K, it is already only 50% of the room temperature tensile strength[(3)], therefore the recrystallization temperature is assumed to be at about this temperature. Consequently the built-up edge which is securely adhered at a cutting speed of 30 m/min, is not securely adhered at a cutting speed of 100 m/min or above because the cutting temperature exceeds the recrystallization temperature and it is believed that the rake face directly contacts chips and the wear of the rake face progresses.

2.3 Tool wear during interrupted cutting

Next, to clarify the tool wear mechanism during interrupted cutting, interrupted cutting was performed by turning a round bar of Inconel 718 with

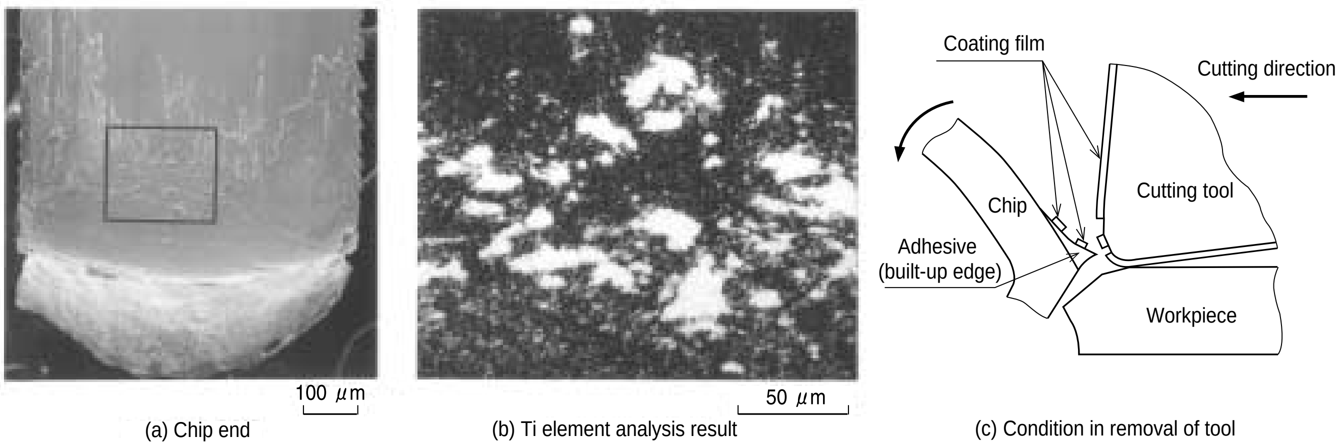
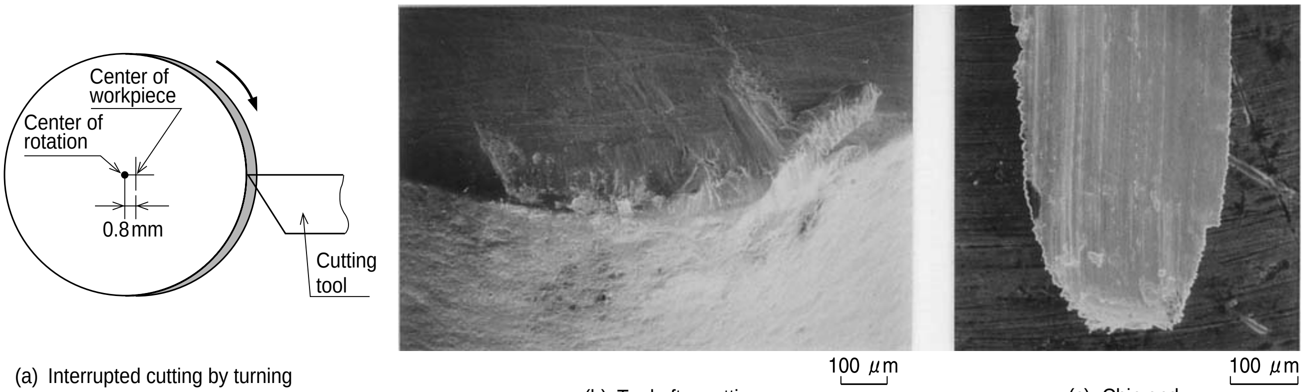


Fig. 6 Chips in interrupted cutting and results of EPMA analysis
Adhesive is transferred to the chip end. The separated coating film of the tool is on that.



(a) Interrupted cutting by turning the eccentric bar
(b) Tool after cutting
(c) Chip end

Fig. 7 Tool and chip in turning an eccentric bar
Adhesive remains on the rake face of the tool. Adhesive is not transferred to the chip side.

a rectangular groove 5 mm wide and 6 mm deep in the longitudinal direction and while cutting, the tool and chips were observed. The cutting conditions were the same for both methods and the cutting speed was 30 m/min. **Fig. 5** shows an SEM photograph of the tool after 5 meters, it was found that adhesive was removed on the rake face of the tool. Also **Fig. 6** (a) shows a SEM photograph of the end of the chips from the rake face and rubbing side at the above time. The streak which would seem to be produced by rubbing with the rake face in the flowing direction to the end of chips, can be seen, yet it is found that the streak is not at the end of chips. From the above, it is believed that the built-up edge adhered to the rake face during cutting was transferred to the chips when cutting was completed. The element analysis of the part shown in the enclosure in Fig. 6 (a) was performed by EPMA to measure the Ti content, which is a composition element of the coating film. The results are shown in Fig. 6 (b). The white areas contain a great amount of Ti. By this figure it can be seen that ununiformly dispersed Ti released by the adhesive, is detected and this is not Ti from the work piece, and this is believed to be Ti included in the coating of tool. It can be confirmed that the coating film had separated.

From the above, it can be seen that during interrupted cutting the adhesive (built-up edge) produced on the rake face is released when the tool is removed from the workpiece and at that time the coating film separates. It is believed that the rake face wear progresses by repeating the above.

The following are the results of our study on the mechanism by which the built-up edge is released.

As shown in Fig. 6 (c), when the tool is removed from the workpiece, chips do not flow out. Consequently slip is not generated between the built-up edge and the chips. Since the compressive force is applied only to the built-up edge, it is believed that the adhesion between the chips and the built-up edge of the same material is stronger than that between the built-up edge and the coating film. Therefore, it is believed that when the chips are separated from the workpiece at the end of cutting, the built-up edge is released with the chips.

3. Measures to improve tool life

Finally, to constrain tool wear caused by coating film separation during interrupted cutting, it is necessary to prevent the built-up edge only from releasing of without coating film, or to prevent releasing only of the built-up edge.

In the former case, improvement of the adhesive strength of the coating film and the tool base material of the cemented carbide is an issue. However, at present such a tool, which has been quantitatively evaluated, has not yet been developed. On the other hand to prevent the built-up edge from being released, there is a cutting method[4] proposed by Usuki et al. in which depth of cut is gradually reduced when the tool is removed from the workpiece. Therefore, as shown in **Fig. 7** (a), the authors used an eccentric round bar of Inconel 718 to turn, and the tool and chip end after cutting were similarly observed. Since an eccentricity of 0.8 mm was given versus the maximum cutting depth of 0.25 mm, as the tool bit into the workpiece, the depth of cut gradually increased from 0 mm to 0.25 mm, and then generally decreased to 0 mm again by the interrupted cutting. Thus, since the depth of cut is set to 0 mm when the tool is removed, the tool is removed almost without compressive force between any chips and the built-up edge.

As shown in Fig. 7 (b), it was found that adhesive remains on the rake face of the tool after cutting. Also, as shown in Fig 7 (c), streaks can be found on the rake face of chips and to the end on the rubbing side and transfer of adhesive to chips could not be found.

From these results it was found in interrupted cutting that if the depth of cut is gradually decreased, releasing of the built-up edge can be prevented and separation of the coating film of the rake face can be controlled. It is believed from the above that during operations such as side cutting by an end mill, groove cutting by a milling cutter, tool life can be extended by using down-cut milling where the unreformed chip thickness is gradually decreased rather than up-cut milling where the tool is removed at a certain unreformed chip thickness.

4. Conclusion

To clarify the wear mechanisms of the coated cemented carbide tools in cutting Inconel 718 super-heat-resistant alloy, continuous and interrupted cutting experiments were conducted and the following results were found.

(1) In continuous cutting at a cutting speed of 30 m/min, the workpiece adheres to the rake face and this adhesive becomes a stable built-up edge and cutting is performed with the rake face protected. On the other hand the adhesive wear progresses in the flank of the tool and the tool life is determined by the flank wear.

(2) In continuous cutting at a cutting speed of 100 m/min or above, adhesive on the tool rake face becomes unstable and wear progresses on both the rake face and flank due to the increased cutting temperature. In particular wear of the rake face progresses quickly and the edge retreats. Therefore, further cutting becomes impossible after cutting only 70 meters.

(3) In the interrupted cutting, when the tool is removed from the workpiece, adhesive (built-up edge) produced on the rake face is released. At that time the coating film separates. Wear of the rake face rapidly progresses through repetition and the tool life ends.

(4) It was verified that releasing of the built-up edge is controlled by gradually decreasing the undeformed chip thickness at the end of cutting and thereby the above separation of the coating film on the rake face can be restrained.

From the above, the process of the tool wear when cutting the super-heat-resistant alloy has been clarified and at the same time a machining method for extending of the tool life was found. In the future, based on the results of this research, optimization of the machining will be conducted and it is expected that we will grapple with higher efficiency in turning, milling and end milling of the parts of gas turbines and airplane engines.

Furthermore, the rotary tool[5] which was developed as an effective tool for high-efficiency cutting has been applied. While clarifying the effect of decreasing the tool wear, high-efficiency of the above parts is promoted. Also it is intended that tools and machine tools enabling high-efficiency cutting of super-heat-resistant alloy be developed.

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