“Peel cutting” – a new cutting method for difficult-to-cut workpieces with hard oxide surfaces ☆

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Abstract

A new cutting method named “peel cutting” is proposed in this research to suppress notch wear in machining of metals with hard oxide surfaces. In general, metals are produced by hot deformation processes like rolling, forging, and extrusion, which cause hard oxide surfaces called scales on their surfaces. These hard scales need to be removed first in machining of precision parts. However, the machining causes the severe notch wear at the depth-of-cut position, where the tool contacts the hard scale. To solve this problem, the proposed peel cutting avoids this direct contact between the tool and the scale by inclining the end cutting edge at an extremely large inclination (oblique) angle. This extremely oblique cutting changes the material flow and generates a “burr-like chip”. In the proposed cutting method, the tool contacts only soft non-oxide metal under the scale during cutting. Cutting of titanium alloy Ti-6Al-4V is conducted by modifying commercial tools to provide extremely large inclination angles, and it is clarified that an inclination angle of 70 deg or greater is required to realize the proposed cutting. Tool wear in the proposed cutting of the alloy with a hard scale is also observed in comparison with the ordinary cutting, and the result verifies that the notch wear can be suppressed successfully by the proposed peel cutting.

Keywords: peel cutting, burr-like chip, oxide layer, scale, oblique cutting, notch wear

1. Introduction

Titanium alloys have been applied increasingly in aerospace industry [1] because of their excellent properties such as light weight, high strength, and high corrosion resistance. Mechanical properties of a titanium alloy Ti-6Al-4V are listed in Table 1. Their application fields have been expanding, for example, to medical equipment, electric appliance and sports equipment, and the demand for titanium alloys has been increasing accordingly. However, the titanium alloys are classified as difficult-to-cut materials since they have low heat conductivity, high strength and high chemical activity at high temperature. Furthermore, hot deformation processes such as hot forging and hot extrusion are commonly applied to roughly shape the titanium alloys before precise machining, and the hot processes cause thick oxide layers called "scales" formed on their surfaces, see Fig. 1. The scale is much harder than the titanium alloy itself. Hardness of the scale is around 1300 HV [2], whereas that of the titanium alloy Ti-6Al-4V is about 335 HV [3]. The hard scale is often removed by cutting process, where the tool needs to cut the hard scale layer and consequently has a severe problem of rapid tool wear. This tool wear occurs in the region where the tool contacts with the scale, that is called notch wear, see Fig. 2 [4]. As a practical example, a conventional bar peeling mechanism is shown in Fig. 3, where the cylindrical surface with the scale is removed by ordinary turning with four rotating cutters [5].

Table 1 Mechanical properties of Ti-6Al-4V

Tensile strength MPa	959
Elongation %	14
Hardness HV	335
Young's modulus GPa	113
Specific strength N·m/kg	220×10^3
Density g/cm^3	4.43
Thermal conductivity W/(m·K)	7.5

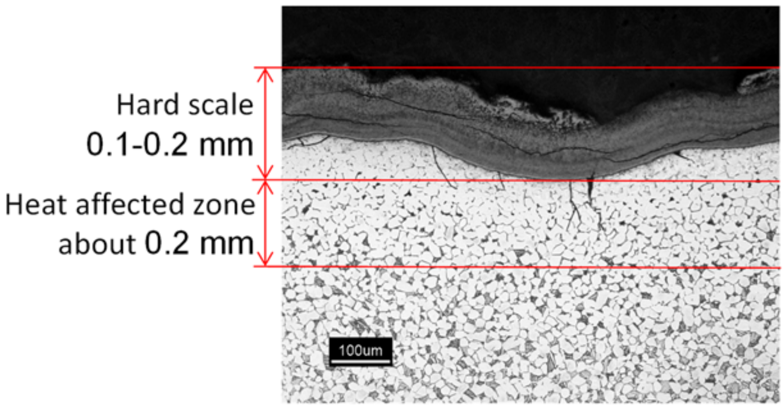


Fig. 1 Microstructure of titanium alloy with hard scale

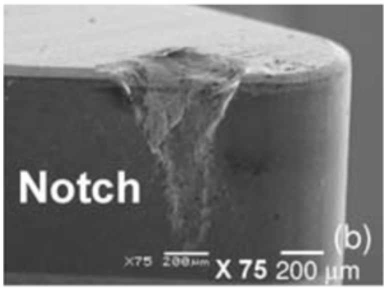


Fig. 2 Notch wear of CBN tool observed after ordinary cutting of titanium alloy [4]

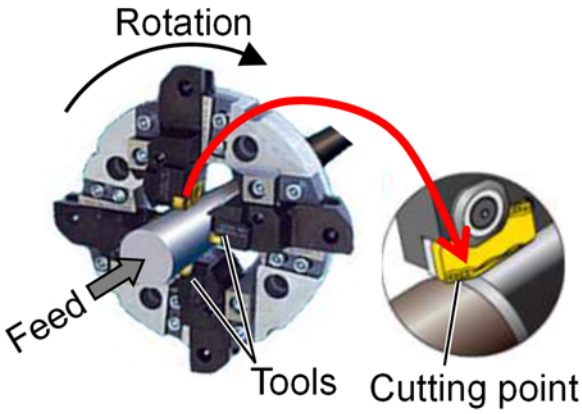


Fig. 3 Bar peeling mechanism which utilizes ordinary turning process [5]

Die shaving or draw peeling (see Fig. 4), in which the entire circumference of a cylindrical surface is removed by one feed motion, can be applied to efficiently remove the hard scale from a small-diameter rod of soft material like copper [6][7]. The tools do not contact with the hard scale in this process, and thus the tools are not worn out rapidly. However, it is difficult to apply this process to titanium rods especially with larger diameters, because it requires extraordinarily high power machines and extremely tough tools for specific diameters. Thus, a new cutting method which does not require either special machines or tools is desirable.

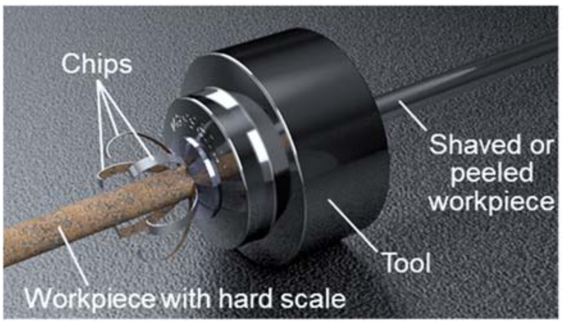


Fig. 4 Die shaving or draw peeling [7]

Another possible approach to machine titanium alloys with the scales is the machining with rotary tools [8]. In this machining process, the wear is distributed to the entire circumference of the circular cutting edge and therefore tool life can be extended. However, the tools contact with the hard scales causing the severe wear, i.e., this process fundamentally has the same tool wear problem.

A new cutting method named "peel cutting" is proposed in this research, where the contact between the tool and the hard scale can be avoided without extraordinarily high power machines or extremely tough tools for specific diameters. In the peel cutting process, the tool cuts and finishes the soft inner part of the workpiece material under the outer hard scale with an extremely oblique or inclined cutting edge, and the tool simultaneously ploughs the cut material to form a "burr-like chip" with another cutting edge. Since the burr-like chip prevents the direct contact between the hard scale and the tool, the notch wear can be suppressed. In this paper, the concept of the peel cutting is explained, and necessary condition to realize the peel cutting is discussed. Subsequently, peel cutting experiments are carried out with a turning center at various inclination (oblique) angles, and obliquity required for the peel cutting is clarified. Finally, the advantage of long tool life in the proposed peel cutting is experimentally verified compared with the ordinary cutting.

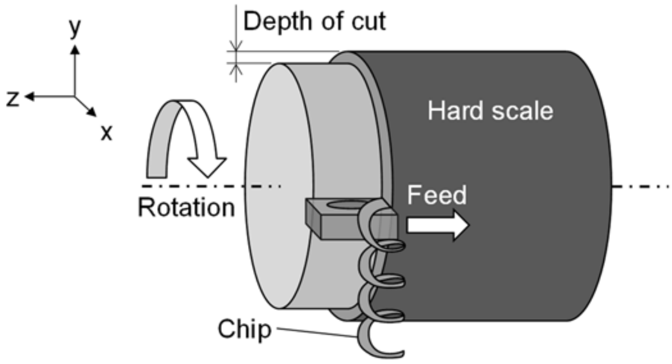
2. Proposal of peel cutting method

2.1. Conventional cutting

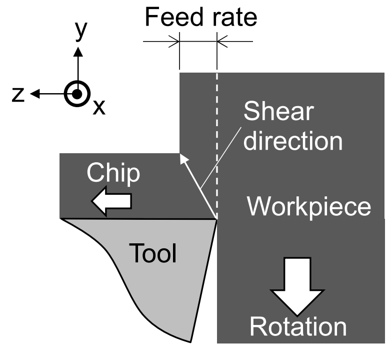
Figure 5 shows schematic illustrations of the conventional cylindrical turning process. In this process, the end cutting edge is roughly aligned with the rotation center of cylindrical workpiece and fed in parallel to the rotation center. The chip formed at the tool tip flows out in the roughly normal direction to the side cutting edge, where the cylindrical surface is finished around one extreme point of the engaged cutting edge and the tool contacts with the hard scale around the other extreme point, as shown in Fig. 5(b). The cutting process, which is seen in the depth-of-cut (x) direction, is shown in Fig. 5(c). The material on the left side of the broken line is removed as a chip, and it flows on the rake face of the tool. It is obvious that the contact between the tool and the hard scale is unavoidable in the conventional cutting, causing the severe notch wear.

2.2 Principle of proposed peel cutting

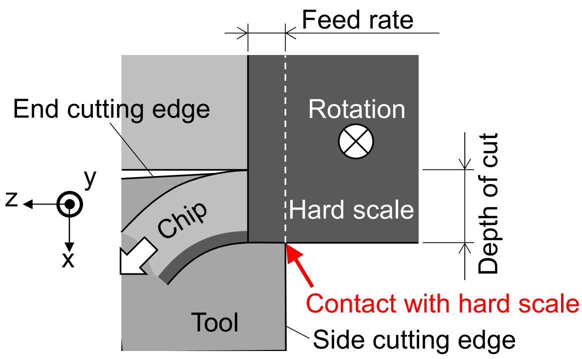
In the proposed peel cutting process, the tool cuts and finishes the inner soft part of the workpiece material under the surface with the end cutting edge which has an extreme obliquity [9], i.e., large inclination angle i, and the tool simultaneously ploughs the cut material to form a burr-like chip with the side cutting edge, as shown in Figs. 6 and 7. Note that the side cutting edge in this process conducts only ploughing without cutting. The burr-like chip formation tends to occur, as the side rake angle is negative with a large absolute value. In the process shown in Fig. 6, the side rake angle γ has the same absolute value as the inclination angle of the end cutting edge, i.e., $\gamma = -i$.



(a) Perspective view



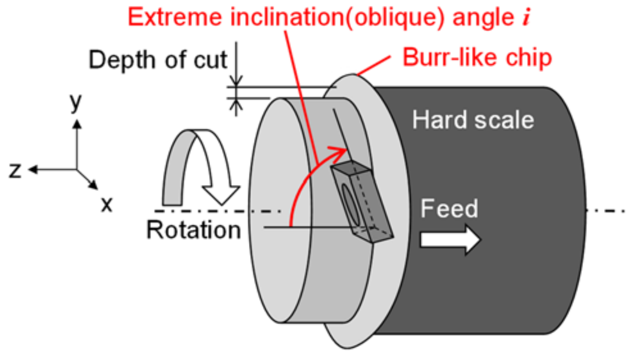
(b) Close-up view in depth-of-cut (x) direction



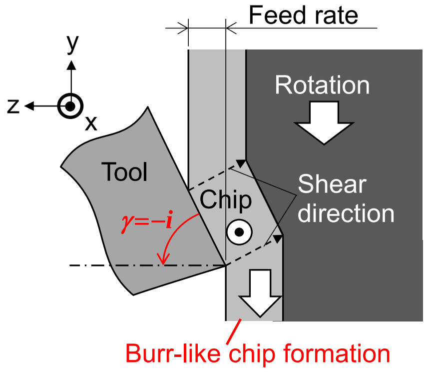
(c) Close-up view in cutting (y) direction

Fig. 5 Conventional cylindrical turning process

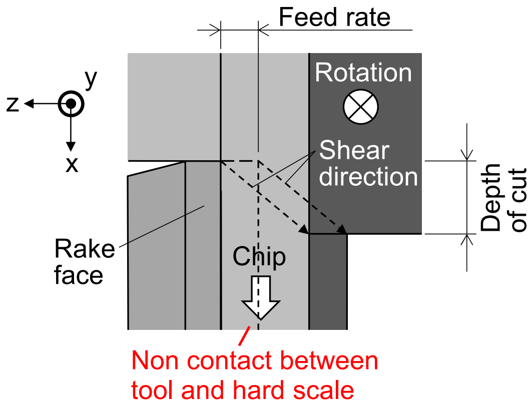
This peel cutting process can be understood as either a new type of cylindrical turning or a new type of die shaving. When understood as a new type of cylindrical turning, the cutting is conducted in the circumferential direction and the material is removed as a burr, i.e., no chip is generated. On the other hand, when understood as a new type of die shaving, the cutting is conducted in the rotation-axis direction and the material is removed as the burr-like chip. In this understanding, the circumferential motion is mainly considered as sidewise motion of the end cutting edge.



(a) Perspective view



(b) Close-up view in depth-of-cut (x) direction



(c) Close-up view in cutting (y) direction

Fig. 6 Proposed peel cutting process

The mechanism of burr-like chip formation can be seen in the depth-of-cut (x) direction and the cutting (y) direction in Figs. 6(b) and 6(c), respectively. They show that the direct contact between the tool and the hard scale is avoided in the peel cutting because the burr-like chip exists between them. As explained above, the burr-like chip is formed in the peel cutting as if the skin of the workpiece is peeled, and hence this process is named "peel cutting". As shown in Fig. 7, there are two additional unique shear zones in the peel cutting compared to the ordinary cutting. The end cutting edge cuts the workpiece material, generates the burr-like chip, and finishes the surface, while the side cutting edge does not cut the material but just ploughs and shears the burr-like chip. The shear zones are simplified to the shear planes in the figure. The main shear plane S_m is generated in the workpiece material from the end cutting edge, the back shear plane S_b occurs in the presently formed burr-like chip from the side cutting edge, and the front shear plane S_f appears in the previously formed burr-like chip in parallel to S_b. Because of the two additional shear zones, the machining force and energy increase in the proposed cutting compared to the ordinary cutting. However, it should be noted that the increment is not so large when it is applied to metal with hard scales as described in the following chapter, since the hard layer is generally brittle and the burr-like chip tends to be broken keeping the two additional shear zones to be small.

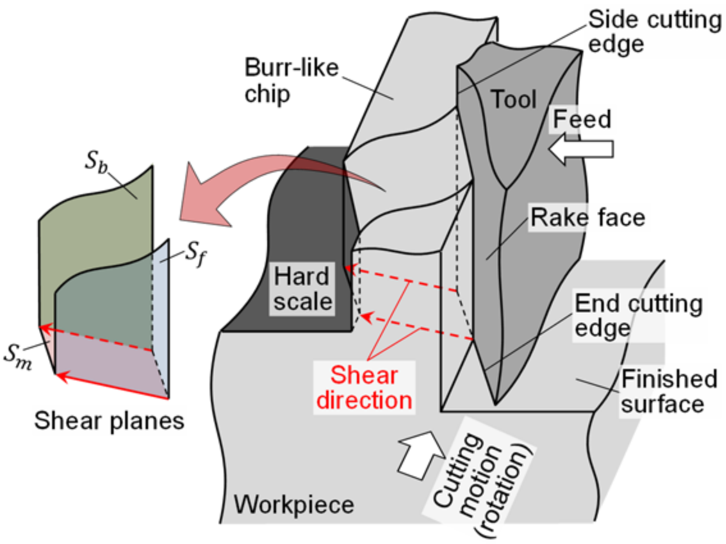
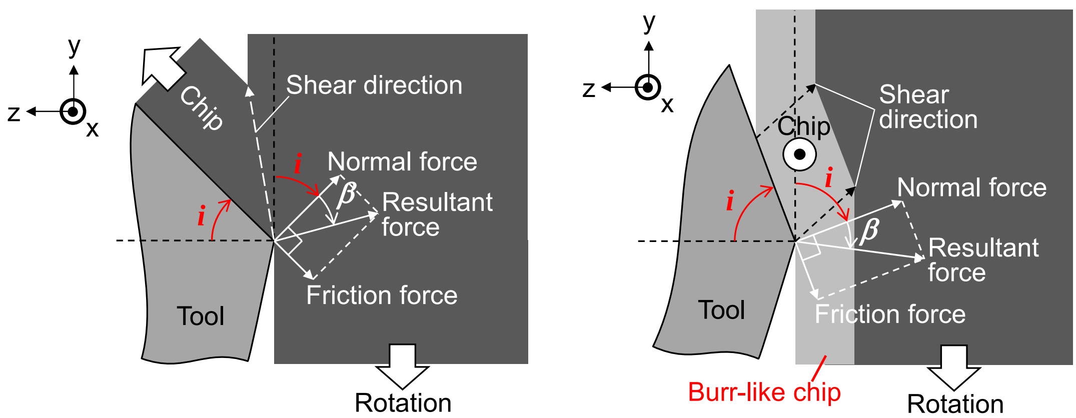


Fig. 7 Perspective close-up view of peel cutting process and unique shear planes



(a) $i+\beta<90$ deg (b) $i+\beta \geq 90$ deg

Fig. 8 Change in material deformation with side cutting edge when i+β exceeds 90 deg

2.3 Condition to realize peel cutting

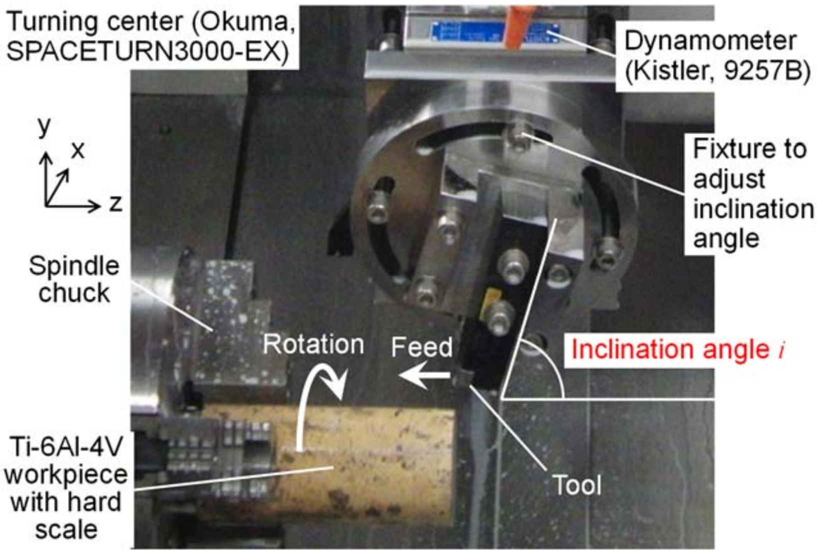
An essential condition to realize the peel cutting is discussed in this section, where the burr-like chip is generated to avoid the direct contact between the hard scale and the tool. As described above, the side cutting edge ploughs the material without cutting in the peel cutting, and basic mechanics of this ploughing process can be explained as follows. When the inclination angle i or the absolute value of side rake angle γ is not large enough, the side cutting edge cuts the material as shown in Fig. 8(a). In this cutting process, the resultant cutting force vector makes an angle i+90+β deg with the z axis, where β is a friction angle between the tool and the workpiece. When the above angle i+90+β is less than 180 deg, it is possible to generate positive shear force for the ordinary chip formation. On the other hand, when the inclination angle i is large enough as shown in Fig. 8(b), the angle i+90+β exceeds 180 deg and hence the shear force for the ordinary chip formation becomes negative, meaning that it is impossible. Instead, the workpiece material is pushed rightward, i.e., ploughed by the side cutting edge, and the peel cutting process is realized as shown in Fig. 8(b). Therefore, a sufficient condition for peel cutting is $i+\beta \geq 90$ deg. The friction angle between the carbide insert and the titanium alloy can be found to be around $\beta \approx 20$ deg [9]. Thus, it is expected that the peel cutting can be realized when $i \geq 70$ deg from this consideration. Note that it is not a necessary condition and the peel cutting may be realized at lower inclination angle i. Furthermore, this critical angle should change slightly depending on the cutting conditions which affect the cutting temperature/tool-chip real contact area and hence the friction angle β.

3. Experimental verification

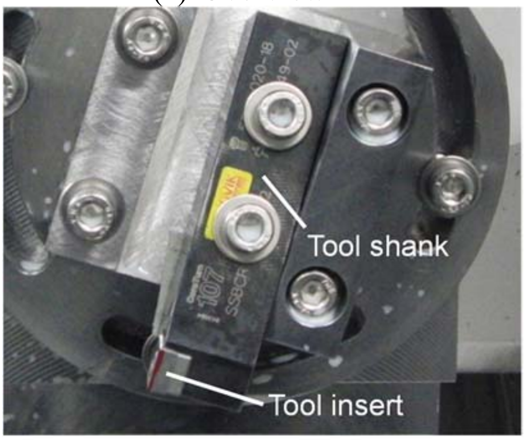
Two series of peel cutting experiments are conducted in this study. In the first series of experiments, the inclination angle of the end cutting edge is varied in order to clarify the condition to realize the peel cutting process, and surfaces of the titanium alloy Ti-6Al-4V without the hard scale are machined so that the change in the chip formation between the peel cutting and the ordinary cutting can be observed clearly. In the second series of experiments, the inclination angle is set to be large enough to realize the peel cutting, and the tool wear (especially notch wear) is mainly compared with the ordinary cutting after cutting of the titanium alloy Ti-6Al-4V with the hard scale.

3.1 Experimental method

Figure 9 shows set up for the cutting experiments. The tool is mounted on a fixture to adjust the inclination angle, which is set on a turning center (Okuma, SPACETURN3000-EX) via a dynamometer (Kistler, 9257B). Commercial non-coated carbide inserts (Sandvik, SCMW120408) are utilized for all the experiments. However, the tool is extraordinarily inclined as shown in Fig. 9, causing the relief angle for the side cutting edge to be extraordinarily large. Therefore, the inserts utilized at large inclination angles for the peel cutting are modified as shown in Fig. 10, i.e., the side cutting edges are ground so that their relief angles become small enough to avoid tool breakage.



(a) Overview



(b) Close-up view of tool

Fig. 9 Experimental setup

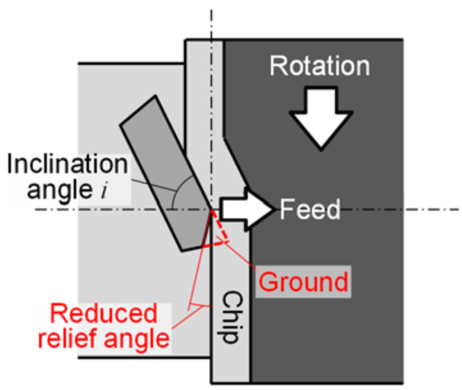


Fig. 10 Modification of tool inserts for peel cutting

3.2 Inclination angle required for peel cutting

The first series of experiments is conducted under the conditions shown in Table 2, where only the inclination angle *i* is varied to clarify the angle required for the peel cutting. The ordinary chips associated with the ordinary cutting process are collected after cutting. Weight percentages of the ordinary chips to the cut materials are measured and summarized in Fig. 11. As shown in the figure, the ordinary chips are generated partially at inclination angles of 60 deg and 65 deg, which indicates that the process is partially the ordinary cutting with large burrs. The ordinary chips disappear completely at an inclination angle of 70 deg as expected in the section 2.3. Hence, it can be concluded that the complete peel cutting process can be realized at an extraordinarily large inclination angle of 70 deg or greater, depending on the friction angle between the tool and the chip. Figure 12 shows examples of the Ti-6Al-4V workpieces with the burr-like chips after the peel cutting. Figure 12(a) shows a beginning of the burr-like chip formation, while Fig. 12(b) shows burr-like chips after growth. As shown, the burr-like chip is broken, as it grows up in the radial direction causing tensile stress in the tangential direction. The chip breakage depends on the tool geometry. For example, the back rake angle α is increased to 10 deg and its effect is demonstrated in Fig. 12(c). It indicates that the burr-like chip is broken into smaller pieces with an increase in back rake angle. Note that the burr-like chip does not grow up like this in practical machining of the titanium alloy surface with the hard scale due to its brittleness as described later in the next section.

Table 2 Experimental conditions to clarify inclination angle required for peel cutting

Workpiece	Material	Ti-6A-4V
	Surface	Without scale
	Diameter mm	50-60
Depth of cut mm		0.6
Feed rate mm/rev		0.05
Inclination angle i deg		60, 65, 70
Back rake angle α deg		0 (10)
Cutting speed m/min		30
Coolant		Soluble (standard dilution)

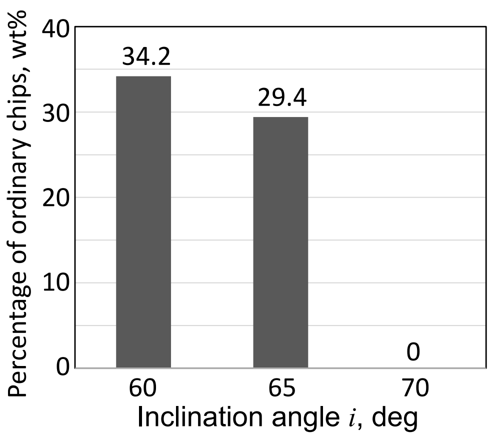
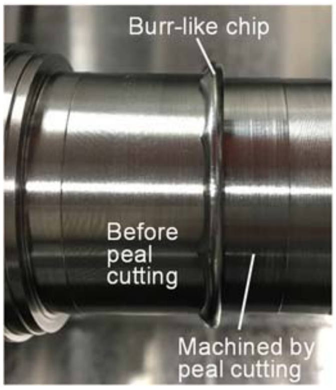
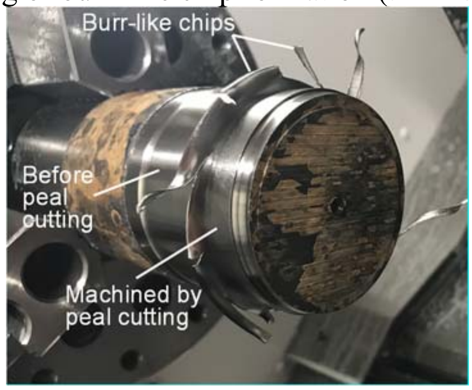
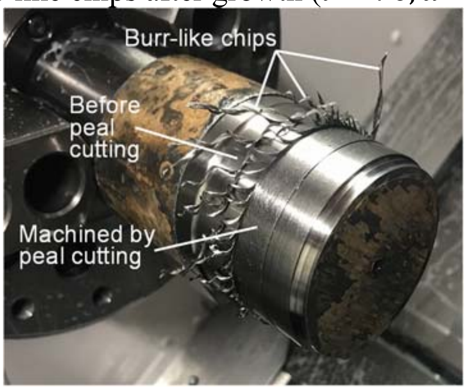


Fig. 11 Percentages of ordinary chips at various inclination angles ($\alpha = 0$ deg)



(a) Beginning of burr-like chip formation ($i = 70, \alpha = 0$ deg)


(b) Burr-like chips after growth ($i = 70, \alpha = 0$ deg)


(c) Burr-like chips after growth ($i = 70, \alpha = 10$ deg)

Fig. 12 Burr-like chips generated in peel cutting of titanium alloy surfaces without hard scale

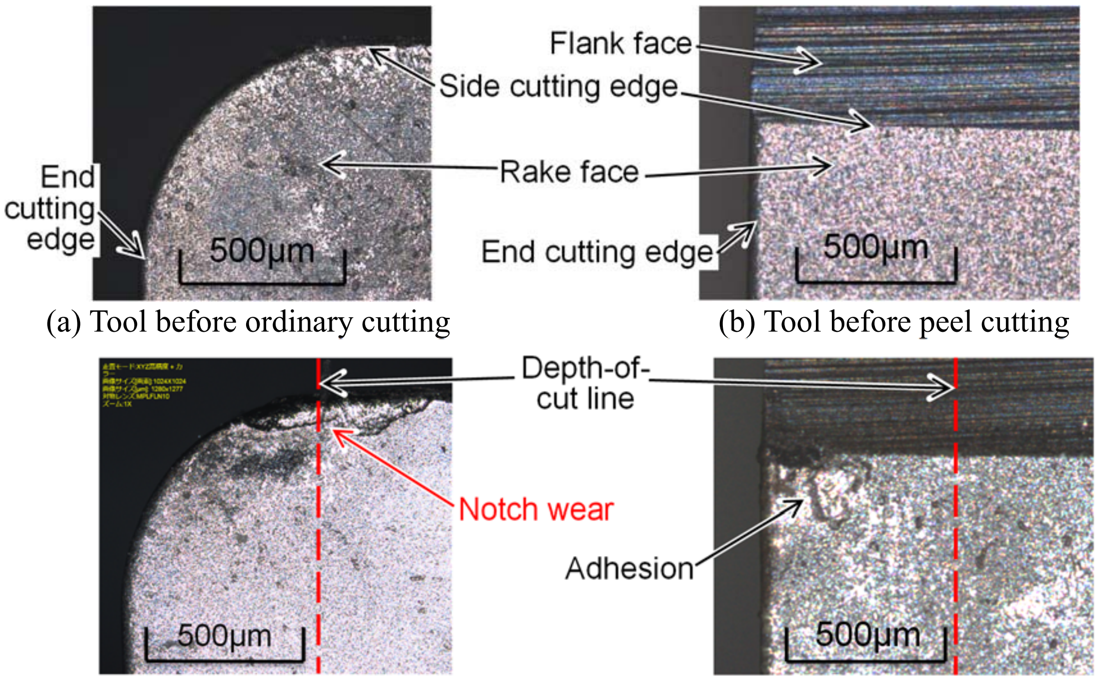
3.3 Tool wear suppression by peel cutting

In the second series of experiments, both the peel cutting and the ordinary cutting of the titanium alloy surfaces with the hard scale are carried out under the conditions shown in Table 3, and the cutting edges are observed with a microscope (Olympus, OLS4100-SAT) after cutting of 800 meters. The inclination angle is kept constant at a sufficiently large angle of 75 deg in order to stably realize the peel cutting, based on the result of the first series of experiments. During the experiments, the cutting force is measured with the dynamometer.

Figure 13 shows microphotographs of the cutting edges taken before and after the cutting experiments. The red broken lines show depth-of-cut lines where the hard surfaces were located before cutting. Noticeable notch wear is observed around the depth-of-cut line on the rake face of the tool after ordinary cutting as shown in Fig. 13(c), while no notch wear after peel cutting as shown in Fig. 13(d). Only a small adhesion exists on the rake face after peel cutting. This difference clearly shows that the notch wear due to the contact with the hard scale can be suppressed successfully by the proposed peel cutting.

Table 3 Conditions for tool life experiments

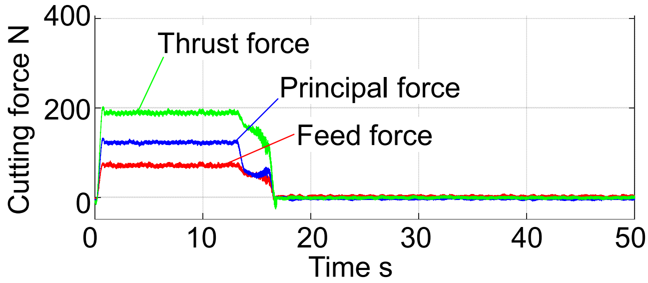
Cutting method		Ordinary cutting	Peel cutting
Workpiece	Material	Ti-6A-4V	
	Surface	With scale	
	Diameter mm	55	
Depth of cut mm		0.6	
Feed rate mm/rev		0.05	
Cutting distance m		800	
Inclination angle i deg		0	75
Back rake angle α deg		0	
Cutting velocity m/min		30	
Coolant		Soluble (standard dilution)	



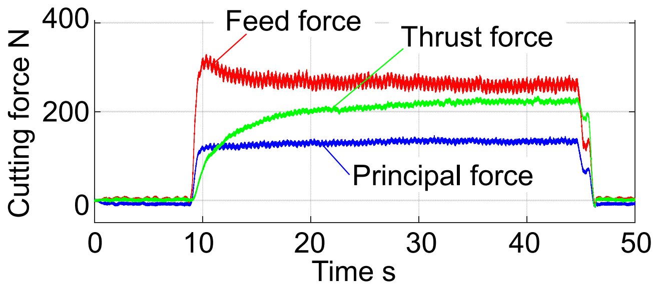
(a) Tool before ordinary cutting (b) Tool before peel cutting

(c) Tool after ordinary cutting of 800 m (d) Tool after peel cutting of 800 m

Fig. 13 Microphotographs of cutting tools before and after tool life experiments



(a) Ordinary cutting



(b) Peel cutting

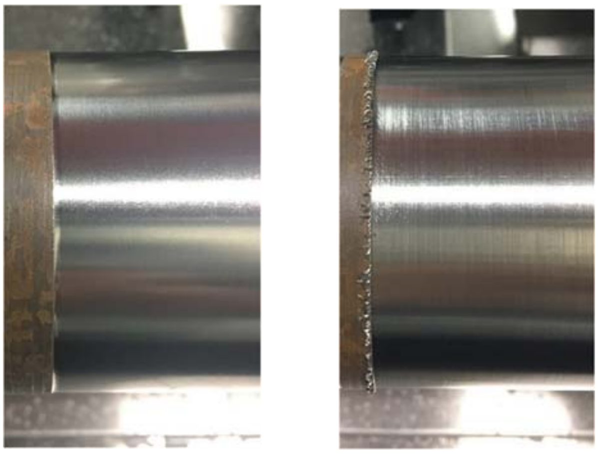
Fig. 14 Cutting force measured during cutting

Cutting force components measured in the principal, thrust, and feed directions during cutting are shown in Fig. 14. Only the feed component is increased in the peel cutting in comparison with the ordinary cutting because of the extreme obliquity and the additional shear zones. As shown in the figure, the principal component, which determines cutting energy, is almost the same, and the thrust component, which mostly affects cutting accuracy, is also similar between the two cutting methods.

The machined surfaces are compared in Fig. 15. Though some burr-like chips can be observed at the end of the machined surface in the peel cutting, see Fig. 15(b), they are much smaller than the burr-like chips generated in the peel cutting of the titanium alloy surfaces without the scale, see Fig. 12. This should be because the chips formed out of the surface with the hard scale are brittle and hence broken away from the workpiece during the chip formation or large deformation. Quality of the surface obtained by the peel cutting is lower than that obtained by ordinary cutting, though it is not a problem for first rough machining of metals with hard scales. A possible reason for the rough surface may be the adhesion of the workpiece material to the cutting edge under the present peel cutting conditions, see Fig. 13(d).

4. Conclusion

A new cutting method, named “peel cutting”, was proposed in the present research for rough machining of various materials covered with hard scales, where direct contact between tools and scales can be avoided by forming “burr-like chip”. To realize the peel cutting with sufficient formation of the burr-like chip, the inclination angle of the end cutting edge is critical, and thus its sufficient condition for the peel cutting was discussed and clarified both theoretically and experimentally. Tool life was also investigated experimentally, and the results verified that notch wear due to the hard scale can be suppressed successfully by the proposed peel cutting.



(a) Ordinary cutting (b) Peel cutting

Fig. 15 Workpiece surfaces after cutting

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