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Cooling performance of micro-texture at the tool flank face under high pressure jet coolant assistance

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ABSTRACT

Micro-texture at the tool face is a state-of-the-art technique to improve cutting performance. In this paper, five types of micro-texture were fabricated at the flank face to improve the cooling performance under the condition of high pressure jet coolant assistance. By using micro-textures consisted of pin fins, plate fins and pits fabricated 0.3 mm away from the cutting edge, heat transfer from the tool face to coolant was enhanced. The conditions of tool wear, adhesion and chip formation were compared between the micro-textured and non-patterned tools in the longitudinal turning of the nickel-based superalloy Inconel 718. As a result, micro-textured tools always exhibited the reduced flank and crater wear compared with the non-patterned tool, and the rate of tool wear was influenced by the array and height of fin. The energy dispersive spectroscopy analysis of worn flank faces and the electromotive forces obtained from the tool-work thermocouple supported better cooling performances of micro-textured tools. In addition, coolant deposition at flank face evidenced that heat transfer could be promoted by micro-texture near the border of the contact area between the flank wear land and machined surface. Finally, the changes of flow patterns with pit depth are analyzed for pit type tools by computational fluid dynamics. This investigation clearly showed the function of micro-textures for increasing the turbulent kinetic energy and cooling the textured tool face.

1. Introduction

Cutting tools in high speed machining of nickel base superalloy Inconel 718 is challenged by severe thermomechanical loading [1] and thermally-induced tool wear [2]. Low thermal conductivity of nickel base superalloy renders the reduced portion of generated heat to be transported away with a chip and conducted to the workpiece, resulting in the increase in heat conduction to the tool and high cutting temperature. Sufficient cooling is necessary for reducing tool wear and extending service tool life. Therefore, the advanced cooling approaches have been intensively studied [3–5].

It is widely known that the geometric complexity of the micro-textured surface is endowed with an ability of increasing heat transfer coefficient of cooling media when it flows over the textured area. Structures made up of fins with certain shapes and arrays, i.e. pin fin matrix-array [6,7], plate fin array [8,9] and pin fin crossed-array [9,10] have been frequently used for cooling in highly thermally-loaded environment. A properly-designed geometry renders the micro-texture to gain a high heat transfer coefficient from the base material to the surroundings and vice versa, owning to the forced convection around fins [10]. In such case, computational fluid dynamics (CFD) is a powerful tool for revealing a link between the micro-texture and flow pattern, which is a critical guideline for assessing the cooling ability of texture. Wide applications of CFD in advanced cooling methods applied in metal cutting [5,11] and investigation of normal/micro-scale heat sink [12–14] have provided practical solutions for visualizing the coolant flowing near cutting tip and flow across a bank of fins, respectively.

In the metal machining, the changes in tribological properties and resulting improvement of tool conditions have been studied using a tool with the structured texture at the flank and rake faces. Pilot studies presented the state-of-the-art technology in enhancing lubrication, and reducing friction force and adhesion at the tool-chip interface using functionalized micro-texture at the faces of non-coated and coated tools [15–18]. However, the function of micro-texture for the enhancement of heat transfer owning to the enhanced coolant flow has not been investigated yet.

This study investigated the influences of micro-texture at the flank face on the cooling performance in the turning of Inconel 718 under the condition of high pressure jet coolant assistance. Five pat-

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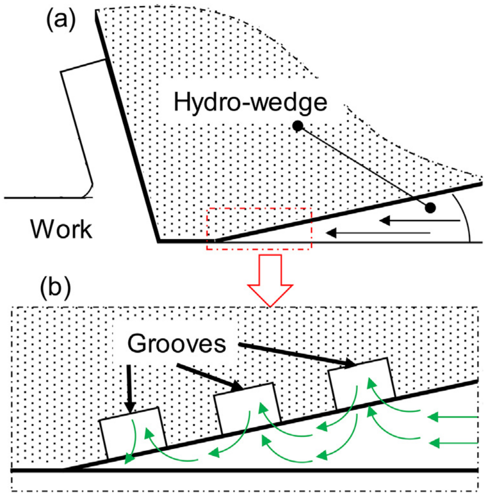

Fig. 1. Micro-texture at flank face. (a) Non-patterned tool. (b) Micro-textured tool.

terns of micro-textures consisted of plate and pin fins and pits were laser-irradiated at the tool flank face. The area of the patterning was 0.3 mm away from the cutting edge so as to avoid tribological alternations at the contact region between the flank wear land and the machined surface. The high-pressure jet coolant was ejected from the side of flank face. The flank and crater wear, chip formation, cutting temperature and adhesion conditions were compared between a non-patterned tool and micro-textured tools. In addition, CFD analysis was used to promote understanding of the role that micro-texture plays in changing the coolant flow.

2. Configuration of experiment

2.1. Micro-textures at flank face

This study attempts to promote heat transfers in cooling flow at the flank clearance within a distance of 1 mm from the cutting edge by fabricating micro-textures. As shown in Fig. 1(b), difference in flow speed in and outside of the texture structure generates local eddies or complicated flow. This would increase the heat transfer from the tool to coolant through the flank face, resulting in the increase in heat transfer coefficient. In such a case, micro-textures with grooves are expected to plays a function of turbulence promoter.

Five patterns of micro-texture fabricated at the flank face are represented as CAD models in Fig. 2. They are classified into three groups, plate-fin arrays, pin-fin arrays and a pit array. Plate fins in parallel and perpendicular to the cutting edge are denoted by “Parallel” or PL and “Perpendicular” or PP, respectively. Square pin fins arranged in a matrix array are denoted by “Dot” or SD, and those in a crosshatch pattern by “Crosshatch” or SC. In addition, concave features can also perform as obstructions and disturbances under high pressure environment, thus square micro-pits in a matrix array are denoted by “Pit” or SP. Dimensions of all the microfins and pits are listed in Table 1.

Table 2
Fin height after laser irradiation.

Nominal height [μm]	Mean fin height [μm]				
	Parallel	Perpendicular	Pit	Dot	Crosshatch
10	14	12	12	12	12
20	23	19	20	18	19

Table 3
Chemical compositions of Inconel 718 in wt%.

Ni	Fe	Cr	Mo	Al	Ti	Mn	Si	Nb	C
53.0	18.5	18.6	3.1	0.4	0.9	0.2	0.3	5.0	0.04

The SEM micrographs in Fig. 3 show the landscapes of the micro-textures fabricated by laser irradiation on the flank face of a PVD coated insert with a single coating layer of aluminum enriched TiAlN. The shape and ISO grade of the insert are CNMG120408 and S05, respectively. The region between the cutting edge and texture area guarantees the observation of flank wear in each cutting application under the same tribological conditions. The textured area covers the corner radius and parts of the major and minor flank faces. The width and interval of fins and pits were always 50 μm. The depth of grooves for making fins and pits were 10 μm and 20 μm. Thus, textures with different fin heights and pit depths of 10 and 20 μm were distinguished by adding “−10” and “−20” to the short name of each texture array, respectively (see Table 1). The surface profiles of the micro-textures were measured with a profilometer. The mean values of fin height are listed for five fin types in Table 2. The thickness of the coating layer was 5.9 μm, thus the coating material was removed and substrate material was exposed after the laser irradiation.

2.2. Experimental procedure

Fig. 4 depicts the schematic diagram of turning operation with a micro-textured tool. Experiments were carried out on a CNC lathe machine tool using a DCLN type tool holder shown in Fig. 5. Thus, the rake and clearance angles of the assembled tool were −6° and 6°, respectively. An inner channel for delivering the high pressure coolant was integrated with the tool holder. Jet coolant was supplied at a high pressure of 13 MPa from a specially made L-shape nozzle on the side of flank face only 8 mm away from the tool tip. The coolant was emulsion type cutting fluid of 10 percent concentration. The flow rate was measured to be 9.2 l/min with a magnetic flow meter installed on a high pressure supply pipe. Because the L-shape nozzle had a cross section of 2.2 mm^2, the flow speed of the coolant at the nozzle was calculated to be 70 m/s.

The workpiece was Inconel 718 of Vickers hardness 568 HV and its standard chemical compositions are shown in Table 3. Cutting conditions were cutting speed 120 m/min, feed rate 0.1 mm/rev and depth of cut 0.5 mm.

Cutting time was fixed at 9 min. The maximum width of flank wear $\mathrm{VB}_{\mathrm{max}}$ was recorded with a digital microscope at certain cutting intervals. SEM and EDS analysis were used to identify the too-chip contact area and adhered materials on the flank face.

Table 1
Dimension of micro-textures.

Group	Texture array	Size (width × length) [μm]	Fin height and pit depth [μm]	Interval [μm]
Plate-fin	Parallel (PL-10, PL-20)	50 × 2200	10	50
	Perpendicular (PP-10, PP-20)	50 × 700	and	
Pit-fin	Pit (SP-10, SP-20)	50 × 50	20	
Pin-fin	Dot (SD-10, SD-20)	50 × 50		
	Crosshatch (SC-10, SC-20)			