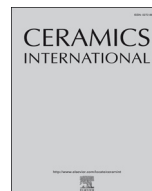




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# Intermittent turning performance of ceramic tools with surface micro-geometry designed considering fluid-like behavior of chip

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## ABSTRACT

This work was performed to study the intermittent turning performance of ceramic tools with surface micro-geometry designed considering fluid-like behavior of chip. Quantitative analysis of the fluid-like behavior of chip was conducted for different cutting length ratios. Ceramic tools with different patterns of micro-textures on the rake face were designed on the basis of the fluid-like behavior of the chip and the skins of dung beetle and shark. An assessment indicator of tool performance was proposed covering external loads and tool microscopic mechanical property. The optimum pattern of micro-texture was distinguished based on the tool performance indicator. Tool lives obtained from turning tests and the values of indicator acquired at varying combinations of micro-texture pattern and cutting length ratio were compared to validate the assessment indicator of tool performance and the design method of tool surface micro-geometry. It was found that the similarity between chip and Newtonian fluid decreased as the chip flowed across tool rake face or the intermittence in turning process became higher. Assessment indicator of tool performance was put forward as the ratio of tool material fracture toughness to the maximum stress intensity factor on the cutting tool. Larger value of the indicator indicated better tool performance. Micro-texture pattern designed with the fluid-like behaviors of different chip zones considered was most efficient in enhancing the tool performance indicator. Experimental results of tool lives demonstrated the correctness of the assessment indicator of tool performance and the effectiveness of the design method of tool surface micro-geometry.

## 1. Introduction

The interaction mode between cutting tool and workpiece is substantially affected by the tool geometry. Tool geometry greatly influences cutting mechanisms, which dominate the tool failure process [1]. Design of tool geometry has become an important aspect for improving tool performance. Optimization of macro-geometry and micro-geometry of cutting tool has attracted great attention. Bionics provided much useful information for the design and optimization of tool geometry especially the tool surface micro-geometry.

Inspired by the excellent friction performance of non-smooth surfaces of animals and plants, many researchers designed and fabricated micro-textures or nano-textures on tool surface to achieve better cutting performance. Many researches on textured cutting tool have been performed in the field of continuous turning. Self-lubricating textured cemented carbide tools were fabricated by Wu et al. [2] and the tool performance in continuous dry turning of Ti–6Al–4V was analyzed. The analysis results indicated that cutting tool with elliptical micro-texture on the tool rake face had much longer tool life compared to the

conventional cutting tool. Kümmel et al. [3] investigated the influences of micro-texture on cemented carbide tool wear in dry turning of SAE 1045 steel. It was found that dimple texture on the tool rake face had better anti-wear performance than groove texture did. Deng et al. [4] studied the performance of cemented carbide tools with different patterns of micro-textures in dry turning. These micro-textures were prepared on rake face of the cutting tool and solid lubricants were filled in them. Cutting tool with elliptical micro-texture was found to have the best cutting performance among all the textured tools analyzed in this study. Micro-texture and nano-texture were prepared on the Al<sub>2</sub>O<sub>3</sub>/TiC ceramic tool surface by Xing et al. [5]. Analysis of tool performance revealed that these textures can be utilized to reduce cutting force, cutting temperature and tool wear. There are also several valuable studies on textured cutting tool used in milling process. Micro-textures were manufactured on rake and flank faces of the cutting tool by Sugihara and Enomoto [6]. The effects of stripe-grooved micro-texture on tool crater wear and tool flank wear in milling were analyzed in this work. It was found that micro-texture can efficiently improve the wear resistance of the cutting tool. Cutting tools with TiAlN coating and

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periodical stripe-grooved micro-texture were developed by Enomoto et al. [7] for face milling of steel. Milling tests indicated that tool wear was substantially reduced due to the texture and coating on the tool surface. Cutting tools utilized in previous researches were mostly cemented carbide tools. It can be found from these studies listed above that investigations of the intermittent turning performance of textured ceramic tools were scant.

The tool-chip contact mode had great effects on mechanical and thermal loads exerted on the cutting tool. It is crucial for the design of micro-geometry on tool rake face to have a comprehensive understanding of tool-chip contact in cutting process. Cutting tool and chip are usually considered to be solid. However, there existed studies by Kwon et al. [8], and Kazban and Mason [9,10] which indicated that chip also exhibited fluid-like behaviors. Therefore, it can be deduced that the fluid-like behavior of the chip should be taken into consideration when analyzing tool-chip contact and designing the micro-geometry on tool rake face. It can be found from former researches on tool surface micro-geometry that the fluid-like behaviors of chip were rarely analyzed and discussed quantitatively.

Tool life is an important benchmark for the performance of cutting tool. Tool failure is closely related to external loads and tool microscopic mechanical property. For the purpose of reducing cost and enhancing efficiency in designing process of the tool geometry, an assessment indicator of tool performance reflecting the complex tool failure mechanisms should be proposed to prejudge tool geometry. However, it can be found from previous studies on tool surface micro-geometry that experimental tool wear or tool life was often used as assessment indicator. The cost was relatively high and it was difficult to efficiently prejudge tool geometry when using experimental results as assessment indicator.

The present work is conducted to investigate the intermittent turning performance of ceramic tools with surface micro-geometry designed considering fluid-like behavior of chip. Ceramic tools with different surface micro-geometries are designed and fabricated based on the quantitative analysis of the fluid-like behavior of the chip. An assessment indicator of tool performance is put forward, in which external loads and tool microscopic mechanical property are integrated. The optimum tool surface micro-geometry is predetermined for different intermittent turning conditions based on the assessment indicator of tool performance. Intermittent turning experiments are performed to validate the assessment indicator of tool performance and the design method of tool surface micro-geometry.

## 2. Numerical simulations and experimental procedures

### 2.1. Numerical simulations

Finite element simulations were carried out for intermittent turning AISI 52100 steel which was hardened to 62 HRC.  $\text{Al}_2\text{O}_3/(\text{W}, \text{Ti})\text{C}$  ceramic cutting tool was utilized. Temperature, stress and strain rate of workpiece and tool were acquired on the basis of simulations. Cutting length  $l_c$  and air-cutting length  $l_{ac}$  were denoted for the workpiece investigated in the work as shown in Fig. 1.  $R_c$  was used to represent the cutting length ratio. It was defined as the ratio of  $l_c$  to  $l_{ac}$ .  $R_c$  was put forward to characterize the intermittence in turning process. Three kinds of workpiece with different values of  $R_c$  (4, 3 and 2) were analyzed in the simulation. Table 1 presents the property parameters of AISI 52100 hardened steel. Constitutive model of the workpiece is crucial for accurate simulation. Metal cutting results in large deformation and excessive heat. Workpiece deformation is greatly influenced by temperature and strain rate. Taking these into account, Johnson-Cook model was applied. It can be described as:

$$\bar{\sigma} = [A + B(\bar{\epsilon})^n] \left[ 1 + C \ln \left( \frac{\dot{\bar{\epsilon}}}{\dot{\epsilon}_0} \right) \right] \left[ 1 - \left( \frac{T - T_{room}}{T_{melt} - T_{room}} \right)^m \right] \quad (1)$$

In Eq. (1),  $\bar{\epsilon}$  is shear strain,  $\dot{\bar{\epsilon}}$  is shear strain rate,  $\bar{\sigma}$  is shear stress and  $T$  is absolute temperature. There are several essential parameters in Eq. (1) such as  $A$ ,  $B$ ,  $n$ ,  $C$  and  $m$ .  $A$  and  $B$  are constants,  $n$  is strain hardening exponent,  $C$  is strain rate sensitivity and  $m$  is thermal softening coefficient. These parameters used for describing the workpiece deformation behavior were adopted from the work by Ramesh and Melkote [11]. The values of these parameters are shown in Table 2.

When the tool was installed on the holder, rake angle of  $-6^\circ$ , clearance angle of  $0^\circ$ , inclination angle of  $6^\circ$  and cutting edge angle of  $90^\circ$  can be obtained. These angles were set for the tool model used in the simulation. Micro-textures of varying patterns were formed on the ceramic tool rake face. Five different patterns of micro-textures were analyzed for each cutting length ratio  $R_c$  in the simulation. Fig. 2 shows the typical micro-textures of different patterns. Micro-texture pattern  $T_A$ ,  $T_B$ ,  $T_C$  and  $T_D$  were the same for different values of  $R_c$ . However, pattern  $T_E$  changed with cutting length ratio  $R_c$  due to the varying characteristics of the fluid-like behavior of the chip. As  $R_c$  varied, the interaction between tool and workpiece changed, resulting in different chip formation mechanisms. Thus, the fluid-like behavior of chip exhibited varying characteristics. Pattern  $T_E$  was designed considering the variation of the fluid-like behavior of chip at different cutting length ratios.  $T_A$  was used to represent the micro-texture pattern for the condition that the tool surface existed without micro-texture. Micro-texture pattern  $T_B$  was constituted of multiple arrays of micro-dimples. Similarly, pattern  $T_C$  contained multiple arrays of micro-grooves. Both pattern  $T_D$  and  $T_E$  had the hybrid arrays of micro-dimples and micro-grooves. However, micro-dimples and micro-grooves were uniformly distributed in micro-texture pattern  $T_D$ . There existed a gradient distribution for micro-grooves in  $T_E$ . The ceramic tool was considered to be elastic. It was also modeled to be heat transfer body. Material property parameters of the ceramic tool under consideration are listed in Table 3.

Geometry of the workpiece shown in Fig. 1 was simplified as shown in Fig. 3(a). Mesh of local region which directly contacted with the tool during cutting process was refined for the workpiece as shown in Fig. 3(a). Local refining technique was also applied for the mesh of cutting tool to refine the region involved in cutting process. Boundary conditions should be determined for the finite element simulation. The bottom nodes of the workpiece were set to be constrained. The tool moved at a constant combination of cutting parameters. These cutting parameters included cutting speed, feed rate and depth of cut.  $v_c$ ,  $f$  and  $a_p$  were used to represent cutting speed, feed rate and depth of cut, respectively. Their values were 80 m/min, 0.4 mm/r and 2 mm, respectively. Metal cutting simulation conducted in the present work focused on dry cutting condition. The initial temperature was set as  $20^\circ\text{C}$ . The resultant cutting forces obtained from simulations and experiments were compared as shown in Fig. 3(b). Relatively small values of the deviations between the simulated and experimental forces validated the metal cutting simulation to some degree.

### 2.2. Experimental procedures

Five patterns of micro-textures were manufactured on the ceramic tool rake face by means of a laser system for each cutting length ratio  $R_c$ . The pulse duration was 10 ns and the wavelength was 1064 nm. Laser power of 3 W, pulse frequency of 40 kHz, scanning velocity of 80 mm/s and scanning times of 4 were applied in the fabrication process of the micro-textures. Intermittent turning tests were carried out on a lathe. Workpiece and cutting tool used in the tests were the same to those utilized in the metal cutting simulation. Cutting parameters applied during cutting tests were also consistent with the simulation. The cutting test was replicated 3 times for each group of the geometry of workpiece and the pattern of tool surface micro-texture. Cutting forces in different directions were examined during the intermittent turning process by the use of a dynamometer (Kistler 9441). The sampling frequency was 4 kHz. A digital optical microscope was applied to

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