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A study on the orthogonal cutting mechanism based on experimental determined displacement and temperature fields

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Abstract

This paper presents a new methodology to study the orthogonal cutting mechanism based on the displacement and temperature fields obtained by the particle image velocimetry technique and thermal infrared imager, respectively. With the displacement and temperature fields as inputs, the thermo-elasto-viscoplastic constitutive model is adopted to calculate the orthogonal cutting strain and stress fields. The formation of built-up edge is detected using the velocity fields. The geometries of the primary shear zone for two different cutting speeds are determined by the strain rate field. The shear stress distributions along the shear plane are obtained according to the calculated results.

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Keywords: Cutting mechanism; Cutting stress field; Cutting temperature; Built-up edge; Particle image velocimetry

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1. Introduction

The physics of metal cutting process are very complex due to the interactions between plastic deformation, heat flow, material damage, friction, vibrations, etc. To understand this process, analytical models have been developed based on some assumptions such as idealized shear plane (Merchant's model [1]), perfectly plastic material (Lee and Shaffer's slip line method [2]). The Oxley's model [3] which has contributed to better results up to day also made some assumptions of parallel-sided shear plane, uniform distribution of stress on the tool-chip interface and uniform temperature distribution on the shear plane. Lately numerical methods such as finite element method [4, 5] and smoothed particle hydrodynamics [6] have been adopted to provide much more realistic results.

Experimental methods such as quick stop method [7], high speed filming [8] and infrared temperature measurement [9], have been used to qualitatively analyze the metal cutting process. To achieve quantitative analysis of metal cutting such as strain and strain rate, grid marking method has been used [10]. Recently, particle image velocimetry (PIV) and digital image correlation have been adopted to obtain the deformation fields without grid marking on the workpiece [11-13].

However, particle image velocimetry and temperature measurement have not been used together to quantitatively understand the metal cutting process including the strain/stress and temperature fields and the stress distribution along the shear plane. To further the understanding of metal cutting process, this paper presents a new methodology to study the orthogonal cutting mechanism based on the displacement and temperature fields obtained by PIV technique and thermal infrared imager, respectively. The strain and stress fields are computed based on the thermo-elasto-viscoplasticity constitutive model with the displacement and temperature fields as inputs. Equivalent strain rate, strain and stress fields are obtained according to the calculated results. The geometries of the primary shear zone (PSZ) and the shear stress distributions along the shear plane for different cutting speeds are extracted.

2. Experimental setup

The cutting tests have been conducted on VMC-C50, a five-axis milling machine center. The experimental setup is based on that of Guo [14]. Some improvements have been made. For instance, the dynamometer and the infrared window are added.

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The experimental setup consists of cutting system, camera-lighting system and thermal infrared imaging system.

2.1. Acquisition devices

A pco.dimax HD camera with CMOS sensor, coupled to a Navitar X12 zoom lens system, has been used for imaging one side of the workpiece at the rate of 2000 fps and the visual image spatial resolution is 2.4 µm per pixel. Two 40 watts LED lights are used to illuminate the scene providing clear images.

The other side of the workpiece has been observed by a Flir A325sc infrared camera with a close-up X1 lens providing a spatial resolution of 25 µm per pixel. Infrared images of 12-bit 320 x 240 pixels can be recorded at rates up to 60 Hz. The workpiece emissivity has been identified using a muffle furnace and a thermocouple with temperature ranging from 100 °C to 500 °C in five points and it is calibrated as 0.03.

The high speed camera and the infrared camera are mounted on the milling machine table and remain stationary with respect to the cutting tool. A complete view of the setup is shown in Fig. 1.

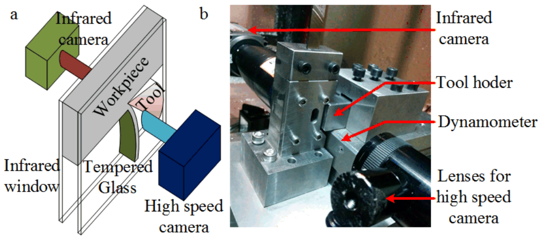

Fig. 1. Principle and structure of the experimental setup.

2.2. Cutting conditions

The workpiece used in this paper is made of nickel-aluminum bronze (NAB) used for marine propeller. The 30 x 12 x 2.5 mm workpiece has been grinded, polished and blasted with micro glass beads to impart some surface irregularities, thus inducing better accuracy in the PIV.

The cutting tool adopted here is made of high speed steel with a rake angle of 6° and a clearance angle of 10.5°. Both side surfaces of the tool have been grinded and polished in order to provide an intense contact with the tempered glass and infrared window which impose a constraint on the work material side flow.

Because of the low frame rate of the infrared imager and the velocity limitation of the machine tool, the cutting velocity *V*, is varied between 2 m/min and 4.5 m/min. Due to the low spatial resolution of the infrared camera (25 µm per pixel), the cutting depth is set as large as 0.3 mm to provide more infrared information.

3. Cutting process modeling

The visual images are processed using the PIV algorithm to get the deformation fields, while the temperature field is easily obtained using the infrared images. The total deformation paths of the work material are obtained according to the velocity fields. The strain and stress fields are calculated based on the thermo-elasto-viscoplastic constitutive model [15] with the displacement and temperature fields as inputs. The Johnson-Cook plastic constitutive model as shown below is adopted to include strain hardening, strain rate sensitivity and thermal softening effects with the assumption of isotropic hardening von Mises yield criteria.

$$\bar{\sigma} = \left(A + B\bar{\varepsilon}^{n}\right)\left(1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^{m}\right) \tag{1}$$

where $\bar{\sigma}$, $\bar{\varepsilon}$ and $\dot{\bar{\varepsilon}}$ are the von Mises equivalent stress, strain and strain rate respectively. T is the temperature of the work material obtained by the infrared camera. The values for NAB are $A = 295$ MPa, $B = 759$ MPa, $n = 0.405$, $C = 0.011$, $m = 1.09$, $\dot{\bar{\varepsilon}}_0^{p} = 1.73\times10^{-3}$ / s and $T_m = 1038$ °C [16]. The reference temperature T_r is 20 °C.

4. Results and discussions

During the cutting process, the high speed camera and infrared camera were used to capture the velocity and temperature of the workpiece material. The captured visual images for two different cutting conditions are given in Fig. 2.

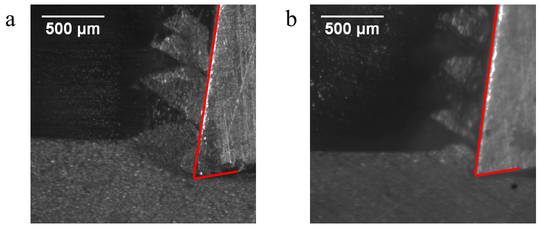

Fig. 2. Visual images for two cutting conditions (a) *V* = 2 m/min and (b) *V* = 4.5 m/min.

Serrated chip generated during the cutting process for both cutting conditions as shown in Fig. 2. In order to make the calculation easier and reduce the computation work, the displacement fields at the start of chip serrating are used for calculating the strain and stress fields instead of that all the displacement fields during the serrated chip formation period are used. The corresponding velocity and temperature fields for two cutting conditions are given in Table 1.

As seen from the velocity fields in the left column in Table 1, built-up edge forms when the cutting speed *V*, is 2 m/min where the velocities in both directions are almost zero. For cutting condition with *V* = 4.5 m/min, built-up edge is negligible as seen from the velocity fields in the right column in Table 1.

Due to the low cutting speed *V* = 2 m/min adopted, the infrared camera successfully captured the serrated geometry of the chip as denoted by the dash-dot lines as shown in the last row in Table 1. Highest temperature for cutting condition with *V* = 4.5 m/min is about 80 °C greater than that of *V* = 2 m/min and it occurs along the chip-tool interface for *V* = 2 m/min. However this is not the case for *V* = 4.5 m/min. Possible reason