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Method of strain-rate difference calculation in high-speed metal cutting

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A B S T R A C T

High-speed machining has been widely studied around the world for its high efficiency and high quality. However, conducting a quantitative study on many physical parameters is difficult when cutting speed is high. A simple and effective measurement and calculation method is necessary in engineering application. From the flow point of view, a difference calculation method through mesh length measurement is proposed, which can be easily used to determine the strain rate distribution of high-speed cutting. The distribution of strain rates for aluminum alloy 7050 cutting has been obtained; the results show that the strain rates are as high as $10^5\ s^{-1}$ during high-speed cutting, and the strain rates near the tool tip are higher than those in other areas in the second deformation zone. In the direction of shear plane, the strain rates are gradually reduced from the center of the first deformation zone to the exterior. The deformation rate in the rake face direction is higher than that in the shear plane direction.

1. Introduction

High-speed metal cutting is a process that ensures high-efficiency and high-quality machining by significantly increasing cutting speed; this process has been widely applied in automotive, aerospace, mold making, and defense industries [1]. The advantages of high-speed machining motivate researchers to investigate this process through theoretical analysis, computer simulation, and experimental confirmation. The research aims to propose predictive performance models to be used in process planning systems for machining processes, with focus on fundamental physical process variables such as stresses, strains, strain rates, and temperatures. Despite efforts to understand high-speed metal cutting, related issues, such as the strain-rate change law, require further analysis. However, for strain rates in the metal-cutting process, real-time measurement is difficult when cutting speed is high, which results in difficulty in conducting a quantitative study on the cutting process.

Deformation, temperature, and strain (rates) during the cutting process are mainly concentrated in three cutting deformation areas. To conduct theoretical analysis of the metal-cutting process, the first task is to establish a theoretical model to correctly describe the parameter change law that occurs in these deformation zones, especially in the first deformation zone; thus, the orthogonal model is proposed. Arrazola et al. [2] reported that modeling of orthogonal cutting continues to dominate research activities in machining because of its relative simplicity. The model that is currently used in the machining process has changed from single-shear plane model [3] to thick-shear zone model [4], which can be used in calculating the strain rates according to the width of the thick-shear zone. However, the shear zone width cannot be measured during cutting. Oxley [5] simplified this problem and supposed that the width of the shear zone is proportionate to cutting thickness, thereby obtaining a formula for calculating the strain rate of the first deformation area; he also pointed out that when the component material being cut passes the first deformation area, the strain rate distribution curve is close to the second curve, which is the highest on the shear plane. However, the value diminishes when it is farther away from the shear plane. This supposition has ignored the effect of material properties and cutting speed on the width of the shear zone in which the increase in cutting speed reduces the shear zone width. Tounsi et al. [6] proposed a strain rate calculation formula on the basis of cutting model at the first deformation area and suggested that strain rates are proportional to cutting speed, inversely proportional to the shear zone width, and correlated with the rake and shear angles of the tool.

Some researchers understand the strain rate law through computer simulation. Finite element method (FEM)-based numerical models are highly essential in predicting chip formation, computing distributions of strain, strain rate, temperatures, and stresses on the cutting edge, as well as in the chip and on the machined work surface [7,8]. Özel [9] obtained the strain rate distribution

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of the shearing zone and the cutting edge; the maximum strain rate obtained by computer simulation was 34,855 s^{-1}. Many researchers [10,11] point out that the strain rate increases during high-speed cutting and reaches as high as 10^5–10^7 s^{-1}. Computer simulation uses two types of analysis, namely, Eulerian and Lagrangian. In Lagrangian analysis, the computational grid deforms with the material whereas in Eulerian analysis, it is fixed in space.

Experimental confirmation is needed to verify the results obtained from theoretical analysis and computer simulation. The various parameters in the process of deformation must be measured and calculated to clarify the formation mechanism of high-speed cutting and to understand the law of changes during deformation. However, in the cutting process, real-time measurement is difficult when cutting speed is high; thus, the root of cutting is normally obtained and used to measure and calculate the various parameters. List [12] marked four streamlines on a chip, obtained the strain rate distribution on the streamlines through stream function calculation, and obtained the strain rate values on the same horizontal line with different angles in the shear zone. The largest strain rate is located at a 45° angle with the streamline. Particle Image Velocimetry (PIV) is a non-intrusive laser optical measurement technique for research and diagnostics into material flow, turbulence, and micro fluidics. With the development of PIV, the metal cutting process can use PIV technology to dynamically observe the changes of various parameters in the cutting process when the cutting speed is not high. Yang et al. [13] and Brown and Saldana [14] used PIV technology to study the deformation and strain rate distribution in the cutting process and obtained the strain-rate distribution conditions of the first deformation area. Experiments and verification are still required if the high-speed cutting process will utilize PIV technology to measure the speed.

Therefore, a proposed simple and effective measurement and calculation method of strain rate in the cutting process is significant in engineering applications. The present article proposes a difference calculation method of strain rate values from the flow point of view based on measurement, which can effectively calculate the strain rate values in the cutting process.

2. Method of strain rate calculation

According to Oxley and Welsh [4], the shear strain rate formula has been obtained through model simplification

$$\dot{\gamma} = \frac{V_s}{\Delta_s}, \tag{1}$$

V_s is the chip slip velocity along the direction of shear plane and Δ_s is the width of the shear zone, as indicated by Fig. 1.

In Fig. 1, V is the cutting velocity, V_c is the chip velocity along the direction of rake face, α is the rake angle, and ϕ is the shear angle. It can be obtained as follows:

$$V_s = \frac{\cos\alpha}{\cos(\phi-\alpha)} V, \tag{2}$$

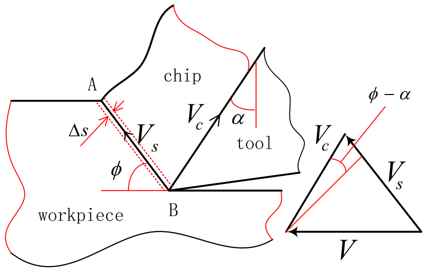

Fig. 1. Orthogonal metal cutting model and velocity vectors.

$$V_c = \frac{\sin\phi}{\cos(\phi-\alpha)} V. \tag{3}$$

The shear strain rate can be obtained as follows:

$$\dot{\gamma} = \frac{\cos\alpha}{\Delta_s\cos(\phi-\alpha)} V. \tag{4}$$

The measurement of width Δ_s is difficult. Oxley supposes that the shear zone width is proportionate to cutting thickness, thereby obtaining the following formula to calculate the strain rate of the first deformation area:

$$\dot{\gamma} = \frac{C_1 V_s}{l_{AB}}, \tag{5}$$

where l_{AB} is the shear plane length and C_1 is a constant that is dependent on material and cutting condition, which is approximately 5.9 as used in their experiments [5].

High-speed machining is a material plastic flow process, from flow aspects. If meshes of specific dimensions are set on the material surface, and the meshes in an area are deformed once they flow to the next area after time t, then the strain rates of both areas can be calculated according to the distance between the two directions.

Direction X is set as the direction along the cutting tool rake face, whereas Direction Y is the direction along the vertical tool rake face, as indicated in Fig. 2. The strain rates along the two directions can be obtained by measuring the deformation of the meshes, and the time of Direction X can be obtained according to the speed and distance of the cutting along the rake face direction. Direction Y can be calculated according to the angle relationship because it is not the same as the sliding direction.

Suppose the length of a mesh in Direction X within a certain period of time is x_{n-1}, the length changes to x_n after t moves in Direction X for distance L_x after a period of time. If adjacent meshes are measured (ignoring the width of the laser-beam machining line), then the distance L_x moving along Direction X is approximately equal to the measurement length x_{n-1} of the first mesh in Direction X. Therefore, the time can be expressed as

$$t = \frac{L_x}{V_c} = \frac{L_x\cos(\phi-\alpha)}{V\sin\phi} = \frac{x_{n-1}\cos(\phi-\alpha)}{V\sin\phi}. \tag{6}$$

The strain along Direction X is

$$\gamma_n = \frac{x_n - x_{n-1}}{x_{n-1}}. \tag{7}$$

The strain rates along Direction X can be obtained as

$$\dot{\gamma}_x = \frac{\gamma_x}{t} = \left|\frac{(x_n - x_{n-1})V}{x_{n-1}^2}\right| \frac{\sin\phi}{\cos(\phi-\alpha)}, \tag{8}$$

and the strain rates along Direction Y can be expressed as

$$\dot{\gamma}_y = \frac{\gamma_y}{t} = \left|\frac{(y_n - y_{n-1})V}{y_{n-1}^2}\right| \cos\alpha. \tag{9}$$

Thus, the strain rate can be calculated by measuring the length of adjacent meshes based on the flow point of view.

3. Experiment design and measurement results

Quick-stop slot milling tests were conducted by using specially designed quick-stop plate samples to obtain the chip root. Material 7050 aluminum alloy was selected; 0.05 mm × 0.05 mm meshes were prepared on the plate surface by femtosecond laser technology, and a series of notches along the same edges has been prepared through wire electrical discharge machining. When the area near the short notch is decreased by the tool feed, the chip root is pushed to break (Fig. 3). This procedure enables easy extraction of the chip root from the sample. Sample cutting is conducted