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Development of metal cutting process accompanied by a localized compressive hydrostatic stress field formation: Examination by molecular dynamics simulation

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ABSTRACT

Improving machined surface integrity is important for precision machining. The aim of this work is to develop a cutting tool, which enables to generate a localized compressive hydrostatic stress field in the vicinity of cutting point to suppress unnecessary plastic flow and to improve the surface integrity of workpiece. In this paper, as the first step a simple cutting tool attached with a laminar jig equipped with a small rectangular hole for cutting chip elimination was proposed, and a molecular dynamics simulation of nano-cutting of monocrystalline aluminum was performed in order to verify and reveal the effectiveness and issues, respectively, of proposed method for improving machined surface integrity. The obtained simulation results were also compared to those using a normal cutting tool in order to clarify the cutting mechanism. As a result, it was clarified that a high compressive hydrostatic stress field was successfully introduced in the vicinity of cutting point. Consequently, the burr formation and elimination of cutting chip were remarkably suppressed and smoothened, respectively by using proposed cutting tool.

1. Introduction

The machining process represented by cutting can lead to damage of the machined surface and subsurface, such as burr, residual stress and so on. It is because the material removal in such a process is mainly carried out by the plastic deformation and subsequent fracture. Therefore, the suppression of unnecessary plastic flow is of considerable importance in the precision machining.

It is commonly known that the hydrostatic pressure causes the plastic deformation [1], even though it affects the deformation behaviors of materials. For example, the yield stress and ductility of many kinds of metals increase under a high compressive hydrostatic pressure [2]. At an atomic level, a high compressive hydrostatic pressure reduces the density of lattice defect such as voids and cracks, and also works to inactivate the mobility of workpiece atoms [3]. Such characteristics are expected to be applicable to higher quality surface machining. It has been reported in some papers that an improvement in the machined surface integrity can be realized when the cutting is conducted under a high compressive hydrostatic pressure condition [4,5]. However, relatively large equipment utilizing the hydraulic pressure is needed to give such a high compressive hydrostatic pressure to the workpiece, and this has been a big issue for practical use.

As a practical method, grinding is effective to give such a high compressive hydrostatic stress field in the vicinity of the machining point due to a usage of abrasive grains with negative rake angles, even though the sharpness in the chip elimination tends to be deteriorated. Therefore, an alternative method for introducing such a high compressive hydrostatic stress field, even if a tool with positive rake angle is used, is considered of value.

The present study aims to develop a cutting tool, which enables to generate a localized compressive hydrostatic stress field in the vicinity of the cutting point to suppress unnecessary plastic flow and to improve the surface integrity of workpiece. In this paper, as the first step a simple cutting tool attached with a laminar jig equipped with a small rectangular hole for cutting chip elimination was proposed, and a molecular dynamics [6] (MD) simulation of nano-cutting of monocrystalline aluminum was performed in order to verify and reveal the effectiveness and issues, respectively, of proposed method for improving machined surface integrity, as well as to clarify the cutting mechanism.

2. Hydrostatic stress and yield condition

The stress at any point in an isotropic material, assumed to behave as a continuum, is completely defined by nine stress

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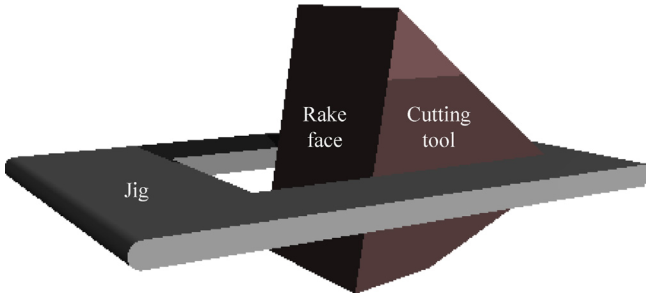


Fig. 1. Proposed cutting tool model.

components and can be expressed as a second-order tensor as follows:

$$\sigma_{ij} = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix} \tag{1}$$

The stress tensor is decomposed into a hydrostatic and deviator stresses. The hydrostatic stress is defined as the average normal stress

$$\sigma_m = \frac{1}{3}\sigma_{ii} = \frac{\sigma_{11} + \sigma_{22} + \sigma_{33}}{3} \tag{2}$$

Hydrostatic stress means the stress components which acts equally in all directions. Even at very high level of hydrostatic stress, no plastic deformation occurs because no shear stress exerts on any crystal plane. The hydrostatic stress only causes the volumetric change in the material.

The deviator stress is obtained by subtracting the hydrostatic stress from the full stress tensor as follows:

$$\sigma_{ij}^{dev} = \sigma_{ij} - \sigma_m \cdot \delta_{ij} = \begin{pmatrix} \sigma_{11} - \sigma_m & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} - \sigma_m & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} - \sigma_m \end{pmatrix} \tag{3}$$

where δ_{ij} is identity tensor. Only the deviator stress produces shear stress and can lead to plastic flow when it exceeds the yield criterion.

The yield criterion by using von Mises yield model is expressed as:

$$\frac{1}{2}\sigma_{ij}^{dev}\sigma_{ij}^{dev} - C = 0 \tag{4}$$

or as a function of the stress tensor components:

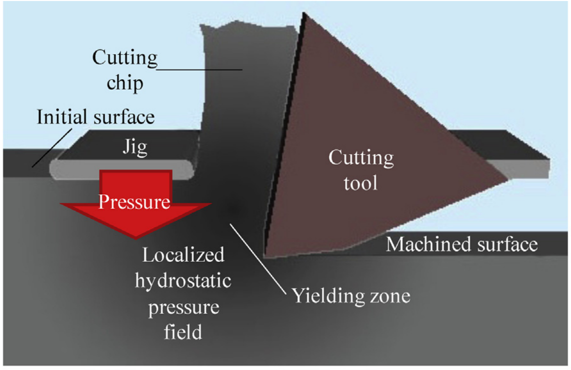
$$\frac{1}{6}[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 + 6(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2)] - C = 0 \tag{5}$$

where C is a constant depending on the yield point of the material. Von Mises yield criterion is isotropic criterion. However, that is in very good agreement with the experimental results of various metals and most commonly used today. From Eqs. (4) and (5), it is also understood that the yield criterion only depends on the deviator stress.

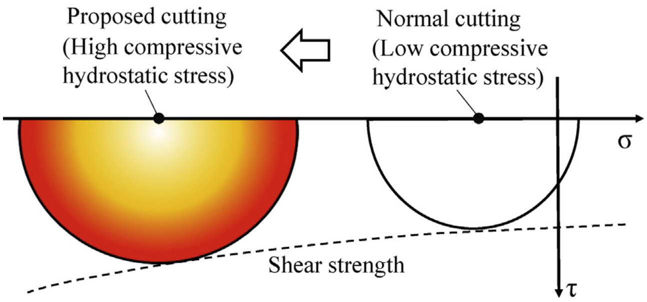
Equivalent stress (von Mises equivalent stress) is defined as:

$$\sigma_\upsilon = \sqrt{\frac{3\sigma_{ij}^{dev}\sigma_{ij}^{dev}}{2}} = \sqrt{\frac{(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{11} - \sigma_{33})^2 + 6(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2)}{2}} \tag{6}$$

which is used to predict yielding of materials under multiaxial loading conditions using results from simple uniaxial tensile. Yielding occurs when the equivalent stress, σ_υ, reaches the yield stress of the material in uniaxial tension.



(a) Cross-sectional view of cutting process



(b) Mohr's stress circle in proposed cutting process

Fig. 2. Schematic drawing of cutting process and stress distribution in proposed cutting method.

Note that, in the latter part, 1, 2 and 3-axis directions are replaced by x, y and z-axis ones, respectively, for clarification of discussion.

3. Proposed cutting model

Fig. 1 shows the schematic drawing of proposed cutting tool. A laminar jig equipped with a small rectangular hole for cutting chip elimination is attached to the cutting tool in order to introduce a localized compressive hydrostatic stress in the vicinity of cutting point.

Fig. 2(a) and (b) illustrates the cross-sectional view of cutting process and the Mohr's stress circle describing inner stress condition when using the proposed cutting tool, respectively. The cutting tool shown in Fig. 2(a) is intended to introduce a high compressive hydrostatic stress field in the vicinity of the cutting point easily by just applying a pressure from the attached jig, even when a positive rake angle is utilized. By using such a cutting tool, the unnecessary plastic flow would be decreased due to an increase in the shear strength (or yield stress) of workpiece [7] as shown in Fig. 2(b), and the plastic deformation would be most likely to occur just under the rectangular hole due to the imbalance in stresses. The most material plastically deformed would be eliminated from the hole as a cutting chip. As a result, the propagation of plastic flow is expected to be decreased as compared to that by the normal cutting.