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A scratching force model of diamond abrasive particles in wire sawing of single crystal SiC

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ABSTRACT

The wire sawing process for single crystal SiC can be regarded as nano and micro scratching on the work-piece with diamond abrasives. The surface/subsurface quality of wafers is affected by the forces in scratching. In this paper, a theoretical force model for nano and micro scratching in wire sawing of single crystal SiC at arbitrary scratching angle is proposed. The geometrical shape of diamond abrasives is discussed and simplified. Then, a primary force model for the simplified abrasive is established considering the interfacial friction coefficient between the abrasive and work-piece. Indention size effect based on strain gradient plasticity theory and elastic recovery are included in this model. Finally, the influences of input variables on the theoretical force under the actual machined depth in wire sawing are discussed. The validity of this model is verified through nano and micro scratching tests in literatures, and the theoretical model matches well with the experimental results.

1. Introduction

Single crystal SiC has been a promising material widely applied in micro-electronic field due to its excellent mechanical strength, good chemical resistance, and high thermal conductivity [1,2]. However, the application requires the SiC wafers with stringent surface and subsurface quality, which remains a machining challenge due to the high hardness and brittleness of single crystal SiC. Wire sawing is the first machining process for wafers and has a great influence on the subsequent process, including grinding, lapping, and polishing [3–5]. Thus, it is important to ensure high surface and subsurface quality of the wafers in wire sawing process.

The average machined depth of abrasives is kept in the range of 0.54–0.72 μm under specific fixed abrasive wire sawing conditions for single crystal Si [6,7]. Therefore, the sawing process can be regarded as nano and micro scratching on the work-piece with diamond abrasives. Theoretical and experimental studies have shown the relationship between normal and tangential forces and cracks induced during indentation and scratching on brittle materials [8,9]. Therefore, it is necessary to analyze the force of abrasives on the wire saw for further investigation of the surface quality of single crystal SiC wafers.

Nowadays, nano and micro scratching tests have been used to reveal the scratching force and machined surface conditions of brittle materials using the AFM-based nano scratching method or nano indenter. The relationship between the normal force applied on the AFM cantilever and the channel depth was established and analyzed both theoretically and experimentally [10,11]. A theoretical force model was developed in nano scratching of reaction bonded SiC with Berkovich and sphere indenters based on interfacial friction coefficient and the ploughing friction coefficient [12]. Besides, the influence of elastic recovery was considered when nano scratching on 6H-SiC using Berkovich indenter [13]. However, the geometrical shape of diamond abrasives on the wire saw does not conform to the indenters mentioned above. Moreover, the indentation size effect on the hardness of SiC cannot be neglected in scratching, especially when the machined depth is relatively small [14,15]. Hence, a new force model considering the geometrical shape of diamond abrasives on wire saw and the indentation size effect is needed.

In this paper, a theoretical force model for nano and micro scratching on single crystal SiC was proposed based on the actual shape of abrasives on wire saw at arbitrary scratching angle. The influences of indention size effect explained by strain gradient plasticity theory and elastic recovery were considered. The effect of input variables on the scratching force under the actual machined depth in wire sawing was discussed, the validity of this theoretical model was verified by experiments in literatures. This paper will provide a better understanding for nano and micro scratching on brittle materials and is helpful to obtain a better surface quality of single crystal SiC wafers in wire sawing process.

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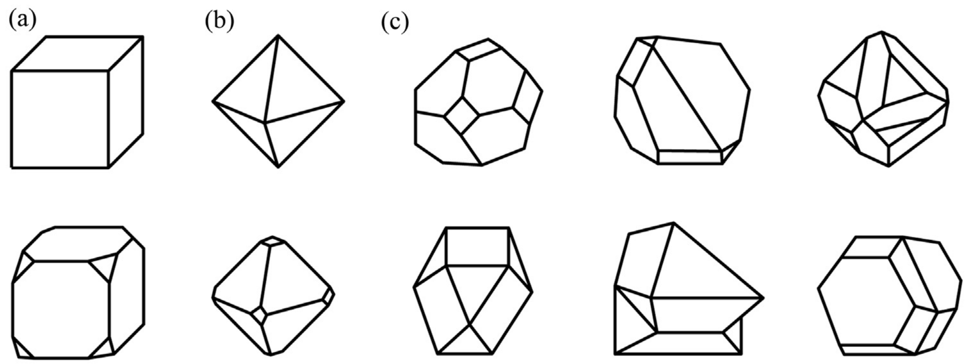

Fig. 1. Three shape series of diamond: (a) hexahedron series; (b) octahedron series; (c) multiply twinned series.

2. Development of force model

2.1. Shape modelling of diamond abrasives

Realistic shape modelling of diamond abrasives on wire saw is a key issue for determining the relationship between the machined depth and scratching force. Based on systematic analysis of the crystal morphology of diamond, the three common shape series can be observed, hexahedron, octahedron, and multiply twinned series, as shown in Fig. 1 [16].

The size of diamond abrasives used in sawing process is within 20–30 μm [17]. The average machined depth of abrasives is kept in the range of 0.54–0.72 μm under the specific wire sawing conditions of single crystal Si, which is rather small compared with the diamond size [6,7]. Therefore, only the geometrical shape of the diamond apex tip is analyzed to establish the force model.

Two kinds of diamond apex tips can be obtained from Fig. 1. The most part is the triangular pyramid shape, next is the rectangular pyramid shape. Three dimensional shape of the diamond abrasive tip was measured by scanning laser microscope, and the tip shape was observed as triangular pyramid. The average angle of centerline-to-face α is 66°, centerline-to-ridge β is 76°, ridge-to-ridge γ is 112° [18]. These three kinds of average angles basically correspond to the angles of regular triangular pyramid with α equaling 66°. Hence, the geometry of the diamond abrasive tip is simplified to a regular triangular pyramid with a spherical crown at the cusp of the tip, as shown in Fig. 2. The angle of centerline-to-face α changes from 50° to 82° [18].

The center of the spherical crown is O with the radius of R. The circular arc with radius r and center O' is the intersection of the spherical crown with the side of the pyramid, which is assumed to be tangent to the edge of the pyramid. I-surface is denoted as the interface of the spherical crown and the surface of the pyramid [19]. Fig. 2(c) shows the section of triangle AO'O. The distance between the apex of the tip and the apex of the ideal pyramid A is described by h^*. The tip is divided into three parts: the sphere part ($0 < h < \Delta_1$), the intermediate transition part ($\Delta_1 < h < \Delta_2$), the pyramid part ($h > \Delta_2$). h^*, Δ_1, and Δ_2 can be calculated by Eqs. (1) and (2).

$$\left.\begin{aligned} h^* &= \frac{\sqrt{R^2-r^2}}{\sin\alpha} - R \\ \Delta_1 &= R - (r\cos\alpha + \sqrt{R^2-r^2}\sin\alpha) \\ \Delta_2 &= R - (r\cos\tfrac{\gamma}{2} + \sqrt{R^2-r^2}\sin\alpha) \end{aligned}\right\} \quad (1)$$

$$\sqrt{(R^2-r^2)}\cot\alpha = \frac{r}{\sin\frac{\gamma}{2}} \quad (2)$$

where the parameters (R, α, γ) to describe the abrasive tip are assumed to be known.

2.2. Primary force model

The contact condition between abrasive and work-piece changes with the included scratching angle θ between the projected line (lateral face edge) AD in normal direction and the scratching direction, as shown in Fig. 3. The base triangle in the top view is denoted as BCD, and A is the apex of the regular pyramid. Only the condition where $\theta\in[0°,120°]$ is discussed due to the symmetry of regular triangle BCD. Moreover, the contact conditions where $\theta\in[0°,60°]$ and $\theta\in[60°,120°]$ are symmetrical about the scratching direction. Thus it is sufficient to analyze the condition where $\theta\in[0°,60°]$.

Fig. 3 shows that the lateral faces ABD and ACD are both in contact with the work-piece in scratching when $\theta\in[0°,30°]$, while only the face ACD keeps contacting when $\theta\in[30°,60°]$.

As discussed in Section 2.1, the abrasive tip is divided into three parts: the sphere part, the intermediate transition part, the pyramid part. Considering the fact that the contact surfaces of the intermediate transition part ($\Delta_1 < h < \Delta_2$) are basically on the lateral surfaces of the pyramid and the value of Δ_2 is relatively small, this part is treated as a part of pyramid approximately to simplify the calculation.

The calculating method of scratching force considering the interfacial friction coefficient between the abrasive and work-piece is applied in this paper [12]. Fig. 4 shows the forces acting on the ideal pyramid when $\theta\in[0°,30°]$. The forces on the contact surface ACD are the normal component F_{nc} which is vertical to the surface ACD, tangential force component F_{tc2} which is parallel to the base edge CD, and tangential force component F_{tc1} which is vertical to the base edge CD on the surface ACD. The angle δ_c is the included angle between tangential force component F_{tc1} and the resultant tangential force of tangential force components F_{tc1} and F_{tc2}. The forces on the contact surface ABD is similar to the case of surface ACD. h_p is the machined depth of the ideal pyramid, ω is the projected angle between line AC and AD in the top view.

The normal component F_{nc} is proportional to the area of the surface ACD.

$$F_{nc} = \xi A_c \quad (3)$$

where ξ is a constant related to the material property and material removal mode, A_c is the area of surface ACD, $A_c = h_p^2\tan(\gamma/2)/cos\alpha$.

The tangential force components can be obtained from Fig. 4.

$$\left.\begin{aligned} F_{tc1} &= \mu_a \xi A_c \cos\delta_c \\ F_{tc2} &= \mu_a \xi A_c \sin\delta_c \\ \sin\delta_c &= \frac{\cos(\omega+\theta)}{\sqrt{1-\sin^2(\omega+\theta)cos^2\alpha}} \end{aligned}\right\} \quad (4)$$

where μ_α is an interfacial friction coefficient, and is taken as 0.05 when the contacting materials are SiC and diamond [12], δ_c is determined by the ratio of the dot products between the two tangential force components vectors and the scratching direction vector.

The forces on the surface ACD can be converted to the forces along the direction of normal force (vertical to the top view) and tangential force (scratching direction) of the pyramid.