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Prediction of sawing force for single-crystal silicon carbide with fixed abrasive diamond wire saw

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ABSTRACT

Fixed abrasive diamond wire saw has been used to cut hard-and-brittle materials into wafers, such as silicon carbide. The force of a single abrasive determines the cutting depth, and affects material removal mode and crack propagation length. Therefore, the sawing force is a key factor that affects the surface/subsurface quality of wafers. In this paper, a numerical sawing force predicting method considering wire saw parameters was proposed with the combination of both ductile removal and brittle fracture removal for each single abrasive. A new calculation method of single abrasive cutting force considering frictional force component and new material removal way considering the effect of lateral crack were adopted. Then the influences of process parameters and wire parameters on sawing force were analyzed. Finally, mathematical sawing force formulas described by both process parameters and wire saw parameters were obtained using the new sawing force prediction method. The validity of this prediction method and sawing force formulas was verified through experiments in the literature under the same process parameters and wire saw parameters.

1. Introduction

Single-crystal silicon carbide 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 high hardness and high brittleness of single crystal silicon carbide is one of the main obstacles for its wide application. Fixed abrasive diamond wire saw was used to slice hard-and-brittle materials into chips with the advantages including thinner kerf, better wafer quality, and higher efficiency [3,4].

The sawing force is a key factor that affects the surface/subsurface quality of wafers, which is of great importance for the subsequent processing [5,6]. The normal force of a single abrasive determines the cutting depth in the scratching of silicon carbide ceramic according to the study of Zhang [7]. There is a relationship between cutting depth and material removal mode [8], and the material removal mode will switch to ductile mode when the cutting depth is below the critical depth [9]. The ductile mode is beneficial to the quality of wafer surface. Besides, the cutting depth affects the crack propagation length when the brittle mode is realized, which determines the surface/subsurface quality of wafers [10,11].

Investigations on sawing force were studied from the macroscopic and microscopic aspects respectively. Liedke and Kuna [12] presented an analytical sawing force model in macroscopic mechanical conditions based on the Preston equation in the free abrasive diamond sawing process. A similar model in fixed abrasive wire sawing process was established by Jia et al. [13] using the same method. These macroscopic models do not consider the material removal mode and cutting ability of different wire saw. Liedke and Kuna [14] developed a numerical model of micromechanical removal process with free abrasive diamond wire saw. The numerical results confirm the phenomenological law of Preston for the removal rate. Microscopic predicting methods were proposed taking into account of the material removal mode which was determined by the cutting depth of each abrasive [15–17]. However, the assumption that the length of lateral crack is assumed to be the size of plastic zone is not suitable compared with the brittle material mechanics, and that the material above the lateral crack is all removed differs greatly with the actual results [18,19]. The calculation of cutting force of a single abrasive only considered the force derived from indentation experiments, which is inappropriate to scratching process [20]. Moreover, the influences of wire saw parameters including density and size of abrasives on wire saw have not been studied and a mathematical cutting force formula considering wire saw parameters is lacked.

In this paper, a numerical sawing force prediction method for wire sawing of single-crystal silicon carbide considering both process

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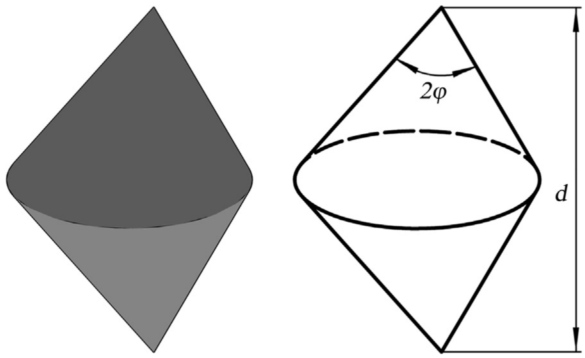

Fig. 1. Dimension of single diamond abrasive.

parameters and wire saw parameters was proposed. Both ductile removal and brittle fracture removal mode of abrasives were analyzed. A new calculation method of cutting force of a single abrasive considering frictional force component and new material removal way considering the effect of lateral cracks were adopted. Finally, mathematical cutting force formulas described by process parameters and wire saw parameters were obtained using the new sawing force prediction method.

2. Prediction procedure of sawing force

2.1. Shape and position of diamond abrasives on wire saw

The shape of diamond abrasive has significant effect on cutting force and crack propagation length in brittle material removal mode [7,19]. In this paper, the diamond abrasive is assumed to be a combination of two cones as shown in Fig. 1 [15,17]. The diameter of the abrasive is d and the cutting tip is assumed to be conical, the half taper angle of which is φ.

The abrasive diameter is assumed to follow normal distribution based on the study of Liu [17]. The maximum diameter is d_{max}, the minimum diameter is d_{min}, and the average diameter is d_{mean}. Thus, $d_{mean}=(d_{max}+ d_{min})/2$. The abrasive size is described by the following probability density function.

$$p(d) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(\mu+log(d))^2}{2\sigma^2}} \quad (1)$$

where σ is standard deviation of abrasive size range, μ is abrasive mean size, namely d_{mean}.

The standard deviation σ is set as

$$\sigma = \frac{d_{\max} - d_{\min}}{6} \quad (2)$$

This calculation for σ is more precise, the abrasive diameter will cover 99.73% of particle size between maximum diameter d_{max} and minimum diameter d_{min}.

The half taper angle is another parameter reflecting the cutting capability of wire saw. According to the measurement of Mahmoud et al. [21], the mean half wedge angle is 55°. In this paper, the half taper angle φ is taken as 55° easy to calculation.

The model of wire saw is established based on the method of Chung [15]. The wire saw is divided into cross sections along wire saw axial direction, and there is only one diamond abrasive on each cross section. Then the distance L between each cross section is calculated as

$$L = 1/(\pi D \cdot \rho) \quad (3)$$

where D is the outer diameter of wire, mm; ρ is the density of abrasives on wire, abrasive/mm^2.

Only the lower half of the wire saw is taken into account due to the reason that abrasives on the upper part are not engaged in cutting. One cross section of wire saw is depicted in Fig. 2. The half circle profile of

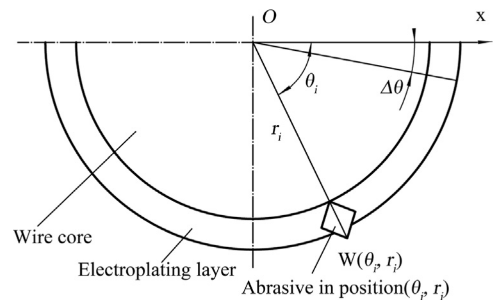

Fig. 2. Cross section of wire saw.

wire saw is divided by N points, that is (N-1) segments, the polar element angle of which is $\Delta\theta=\pi/(N-1)$. The number N adopted in this paper is 1801. The abrasive existence probability of each point is $1/N$, and if there is an abrasive, the size of the abrasive follows probability density function $p(d)$. The coordinate value of wire saw in polar coordinate system is (θ_i, r_i).

2.2. Cutting force of a single abrasive

Cutting force of a single abrasive is essential to the removal of material and therefore to the prediction of sawing force in the whole sawing process. Cutting force can be separated into two parts, cutting deformation force part and frictional force part [22]. However, most proposed calculation method of cutting force only considered cutting deformation force derived from single grit indentation experiment and neglected the frictional force part which must be considered in scratching process [7].

A new cutting force calculation method composed of frictional force part proposed by Zhang [7] was used in this paper, and the forces in the infinite element region Ar between abrasive and the work-piece when scratching are shown in Fig. 3. Ar is the infinite element region on the tapered contact surface between abrasive and the work-piece, and the area of Ar is ds. The forces in the region Ar are the normal component dF_n which is vertical to the infinite element region Ar, tangential force component dF_{t2} which is tangent to the circular cross section of the conical abrasive in the region Ar, and tangential force component dF_{t1} which is vertical to dF_{t2} in the region Ar. α is the included angle between tangential force component dF_{t2} and the resultant tangential force of tangential force component dF_{t1} and dF_{t2}. φ is half taper angle of the abrasive. h is the cutting depth.

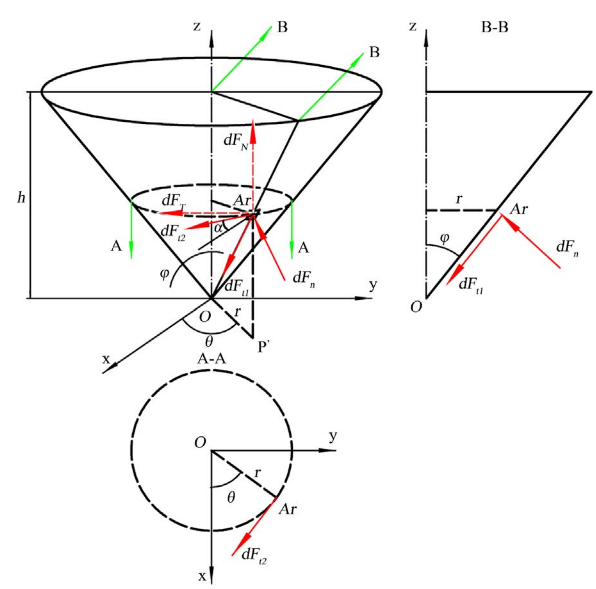

Fig. 3. The schematic of forces on a single abrasive.