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Original Research Article

# Analytical modeling of ground surface topography in monocrystalline silicon grinding considering the ductile-regime effect

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ABSTRACT

Grinding process of monocrystalline silicon easily leads to fractured surfaces, therefore an analytical model of the ground silicon surface is presented. In the model, the ductile-regime effect is considered by determining grain-workpiece interaction mode (ductile and brittle modes) at each grinding moment. Validation experiments proved that the model can, to a large extent, describe realistic silicon grinding and predict the machined surfaces in terms of (i) brittle and ductile area, (ii) roughness and waviness, and (iii) potential chipping zone sizes. The model therefore is anticipated to be not only meaningful to guide and optimize the industrial silicon grinding process, but also transferable to other kinds of brittle materials.

## 1. Introduction

Monocrystalline silicon is a key kind of fundamental semiconductors in engineering, and has been widely-utilised in many electronic or optical products. Silicon product quality is determined by manufacture process, and among all the processing techniques grinding is of great importance, because it is the last "rough" machining step [1]. However, silicon grinding easily leads to fractured ground surfaces with micro-cracks, dislocation, or phase transformation [2]. To this end, many studies have been performed to investigate the ground silicon surfaces obtained by grinding process.

Lee et al. [3] found that, a slight difference of grinding conditions would lead to different ground surface integrity including roughness, waviness and crack numbers, therefore theoretical models of the ground silicon surface were highly desired. Pei and Strasbaugh [4] gave detailed influence regulations of grinding conditions on the ground surface: high wheel and workpiece speeds, shallow cut depths, and fine abrasive sizes tended to produce more smooth surfaces. A series of studies [5,6] also found that, the ground surface roughness can be an indicator of subsurface damage, therefore predictive methods of ground silicon surface roughness was in-demand, especially for manufacturing engineers. The study that had profound meaning is the discovery of the ductile-regime effect [7]: except for brittle fractured fragments, elastroplastic deformations might also happen on silicon surfaces when machining conditions were proper, i.e. material was removed by ductile chip flows. Zarudi et al. [8] attributed this effect to the phase transformation (diamond cubic silicon to metallic phase) ahead of cutting abrasives. Li et al. [9] simulated ground metal surface by regarding grinding as a time-dependent process and determining grain-workpiece interactions (rubbing, plowing and cutting).

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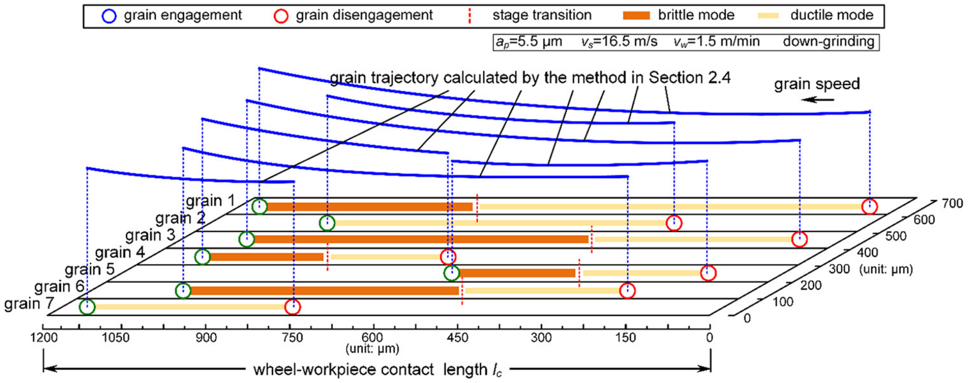

**Fig. 1 – Different grain experiences for the grains having different protrusion heights.**

Based on above, it can find theoretical models of the grinding-induced silicon surfaces has been rarely reported, although it is the foundation of silicon-grinding technique [2].

To fill this gap, an analytical model of the ground surface topography with morphological details is presented in this work. In the model, the ductile-regime effect [10] is taken into consideration. Silicon grinding trials are performed to validate the model feasibility and accuracy. Discussion of the validation results and further discussion about influence of grinding force and temperature are presented in the end.

## 2. Theoretical analysis

### 2.1. Background

Because abrasive grains in grinding wheels are stochastic in terms of sizes and locations [11], therefore each grain has different protrusion heights, which means each grain would experience different grinding modes from grain engagement to disengagement. As seen in Fig. 1 (the figure is achieved by grinding geometrics in Section 2.4 and a grain-specimen interaction determination strategy Section 2.5), some grains may experience both ductile and brittle modes while others may only experience a single mode. Besides, each grain engagement, disengagement, and ductile-brittle transition positions are also varied for each grain. Moreover, in the ductile mode, silicon is removed by plastic flows, while in the brittle mode, the material removal is realized by fractured cracks.

### 2.2. Model framework

The proposed model includes four steps as Step (i) to (iv) in Fig. 2.

### 2.3. Grinding wheel modeling

The modeling procedures proposed in Refs. [3,12,13] are employed here, i.e.

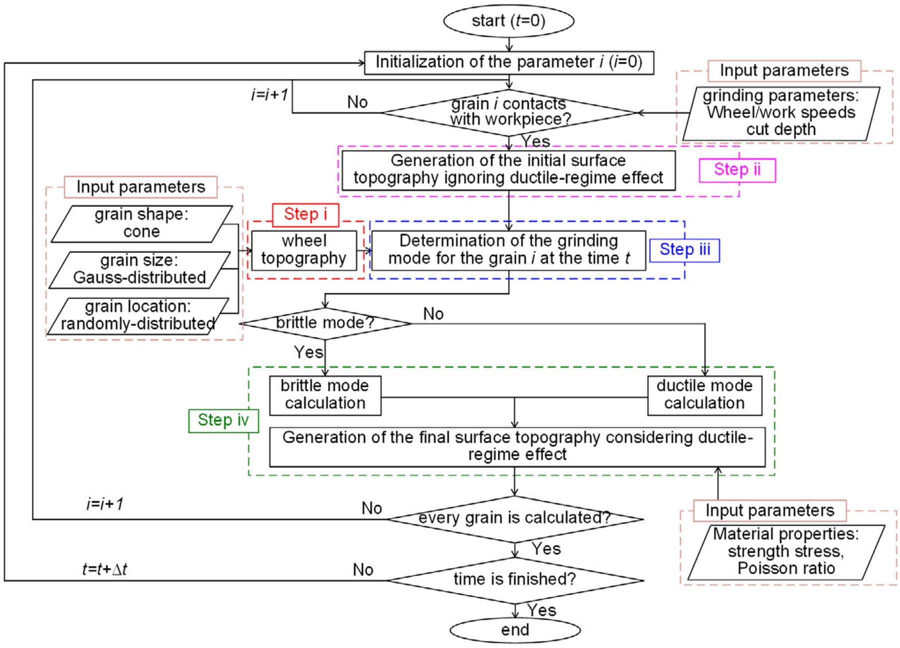

**Fig. 2 – Framework of the proposed analytical model.**