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ORIGINAL ARTICLE

Understanding the mechanism of ultrasonic vibration-assisted drilling (UVAD) for micro-hole formation on silicon wafers using numerical and analytical techniques

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Abstract

This study investigated the mechanism of UVAD using numerical and analytical techniques. Silicon wafers possess challenging cutting properties due to their inherent brittleness and susceptibility to cracking along specific crystal orientation. Hence, non-traditional cutting methods like UVAD hold promise for precision micro-hole drilling in silicon wafers. In order to comprehend the mechanism of UVAD, the numerical technique utilized a direct brittle micro-cracking model within a 2D finite element (FE) method. This facilitated a comparative analysis between conventional drilling (CD) and UVAD, with a specific focus on understanding the micro-cracking mechanisms during the mechanical process. This study examined primarily the cutting force, micro-fracture analysis, and cutting energy. The numerical technique effectively predicted micro-cracks within the brittle regime, a task that is challenging to accomplish using analytical methods alone. In parallel, an analytical technique was developed to predict brittle-ductile transition (BDT) lines by analyzing the thrust force and specific cutting energy (SCE), combined with the numerical technique. Various feed rates per revolution were tested to validate the analytical force predictions. The analytical results demonstrate that the force profile corresponds to the transient cutting depth, while the numerical results indicated that the direct brittle micro-cracking model effectively demonstrated the fracture mechanisms, particularly at greater depths of cut. The SCE graph can predict the formation of a ductile regime on the cutting surface of the drilled micro-hole, although predicting micro-fractures on the side edges of the drilled micro-holes remains challenging. Additionally, UVAD demonstrated a reduction in micro-fractures on the sides of drilled micro-holes, particularly at very low feed rates per revolution.

Keywords Numerical · Analytical · Micro-cracking · Drilling · Vibration-assisted · Micro Hole

1 Introduction

Silicon wafers are used widely in micro-chip production as semiconductors, transistors, or MOSFET devices [1]. In addition to electronic applications, silicon materials also have other applications, including energy, biology, and physics; for example, monocrystalline silicon has been used in solar cells with doped ZnO films [2], cancer treatment with porous silicon [3], and sensor technology [4]. The number of silicon manufacturing processes has increased because of the strong demand for silicon applications [5]. On the other hand, the manufacture of silicon is difficult because of its brittle characteristics [6]. Conventional silicon manufacturing using sawing/cutting a silicon ingot to become a thin disk-shaped silicon wafer is already acceptable as a manufacturing standard. Nevertheless, the last process of the silicon wafers, for instance, flattening, etching, and polishing, is required before sending it to the customer [7]. A non-traditional cutting becomes an alternative process, which can be used as a secondary step cutting process after slicing the silicon ingot, e.g., abrasive wire cutting [8], laser ablation [9], plasma dicing [10], or laser drilling [11].

In silicon cutting, the ductile-like-cutting regime is essential during the cutting process. The ductile-like-cutting regime during silicon cutting was investigated by implementing a tiny amount of cutting depth about several nanometers (< 40 nm) [6]. A brittle-ductile transition (BDT) lower than the critical depth is critical to cutting silicon material to obtain the ductile-like-cutting regime. Another publication

Extended author information available on the last page of the article

reported that the limit chip thickness was approximately less than 10 nm for BDT [12]. Nevertheless, the minuscule cutting depth requires high accuracy and precision machine tools. Furthermore, the extremely low cutting depth leads to less efficiency in the cutting process, particularly the cutting time. A vibration-assisted cutting (VAC) helps enhance the critical cutting depth [13]. The critical cutting depth of BDT was approximately 360 nm when VAC was induced. In contrast, the critical cutting depth was only 38 nm for ordinary-cutting [13], which means significant improvement for VAC. Furthermore, Zhang et al. [14] explored a model of the limit cutting depth of a BDT for VAC. The SCE is a primary key to determining the essential cutting depth threshold in VAC during brittle cutting.

Since VAC has been introduced in standard mechanical processes, for instance drilling [15], grinding [16, 17], milling [18], and turning [19], more scientific investigations or reviews have been carried out [20–25]. In the case of UVAD of silicon or brittle material, there is little literature for that drilling case available. Tsui et al. [26] examined the micro-drilling on a silicon wafer using an ultrasonic vibration-assisted method to the workpiece holder. The chipping area obtained by the ultrasonic vibration method was smaller than with other methods. On the other hand, insignificant improvement in the chipping area using UVAD was obtained under the lowest feed rate of 5 µm/min. Under a low feed, the ductile regime was already attained even without ultrasonic vibrations. The mechanism and insignificant physical understanding of the cutting process were insufficient in their study. Zhu et al. [27] implemented vibration assistance during diamond cutting to produce a circular micro-groove on a silicon wafer. The critical cutting depth was approximately 745 nm using VAC. The vertical cutting ratio and forward feeding ratio should be selected carefully during the circular micro-groove process.

The UVAD has been examined comprehensively for ductile materials instead of brittle materials [28–30]. UVAD is a non-traditional technique that enhances conventional drilling by inducing ultrasonic vibrations onto the drill tool. The high-frequency vibration involves the cutting process, which is generally in the range of 20–50 kHz [20], to increase the capability of the drilling tool, e.g., decreasing the wear of the drill-bit [31]. McMaster University [28] focused on the thrust model during aluminum 6061 drilling. Although the frequency was low (4–12 kHz), their model considered the variations in dynamic uncut chip thickness and the influence of plowing forces, which proved beneficial during the preliminary investigation. Yang et al. [30] elaborated the drilling-force model under a low rotational-speed of 800 rpm with small oscillations (1.5 and 2.5 osc/rev). Yang's model considered the dynamics in the kinematic model, geometry of the drill-bit, bouncing force, and indentation. According to Yang et al. [30], it was impossible to model accurately because of the low stiffness of the shaky rigid parts. Therefore, research the UVAD in a brittle material is still challenging, e.g., force prediction.

The finite element (FE) is a useful technique to examine the process mechanism that is difficult to examine experimentally, e.g., temperature, strain, and stress in the deformation zone [32]. In previous studies [33, 34], the FE model has been used in the brittle cutting mechanism. Zhang et al. [33] examined diamond cutting silicon using FE analysis considering the tool rake angle effect. The FE simulation utilized the DP (Drucker-Prager) constitutive model. The BDT was approximately 118 nm when the negative rake was – 15°. Liu et al. [34] conducted FE simulations during single-crystal silicon cutting. Their study utilized the JC (Johnson–Cook) constitutive model. The cutting heat, cutting force, and chip formation were studied systematically, and a general conclusion was offered. Other researchers used the FE model in elliptical-vibration for reaction-bonded silicon carbide (RB-SiC) [13]. The constitutive model for both SiC and Si was the DP model. The critical depth in that case was between 350 and 400 nm for the BDT.

Cheng et al. [35] proposed a novel model for predicting undeformed chip thickness, which is crucial for analyzing the irregular chips produced in ultrasonic vibration-assisted face grinding. This model considers the effects of elastic–plastic deformation and the trajectory of the grain movement. Their findings indicate that the brittle-ductile transition occurs between 0.31 and 0.35 µm. Kang et al. [36] investigated the material removal mechanism in non-resonant vibration-assisted magnetorheological finishing (NVMRF) of silicon carbide (SiC), focusing on enhancing finishing efficiency and surface quality. Their approach combined theoretical modeling, simulation, and experimental investigation. The study revealed that the maximum depth of subsurface damage achievable post-process is approximately 4.11 µm. This suggests that the diamond abrasives maintain stable contact for an extended period, facilitating better the removal of burr on the material. Li et al. [37] conducted research on the scratching method employed in ultrasonic vibration-assisted single diamond scratching of silicon wafers. They observed that the scratching speed has a minimal impact on the magnitude of the scratching force, whether in conventional or vibrational methods. However, the scratching force is notably higher in the vibrational method compared to the conventional method, attributed to the introduction of ultrasonic vibration.

According to the review above, there was no specific study regarding the brittle drilling mechanism when mechanical vibration is induced in the drill tool. Therefore, this article proposes the FE model during UVAD. The proposed FE model was developed as a 2D mechanism. Later, it was validated in the UVAD during micro-hole drilling of silicon wafers. The variation of cutting speed, cutting depth,