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Experiment and simulation study of laser dicing silicon with water-jet

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ABSTRACT

Water-jet laser processing is an internationally advanced technique, which combines the advantages of laser processing with water jet cutting. In the study, the experiment of water-jet laser dicing are conducted with ns pulsed laser of 1064 nm irradiating, and Smooth Particle Hydrodynamic (SPH) technique by AUTODYN software was modeled to research the fluid dynamics of water and melt when water jet impacting molten material. The silicon surface morphology of the irradiated spots has an appearance as one can see in porous formation. The surface morphology exhibits a large number of cavities which indicates as bubble nucleation sites. The observed surface morphology shows that the explosive melt expulsion could be a dominant process for the laser ablating silicon in liquids with nanosecond pulse laser of 1064 nm irradiating. Self-focusing phenomenon was found and its causes are analyzed. Smooth Particle Hydrodynamic (SPH) modeling technique was employed to understand the effect of water and water-jet on debris removal during water-jet laser machining.

1. Introduction

Due to its excellent mechanical and electrical properties, silicon is widely used as a substrate in photo voltaic, electronic and many high density system applications [1]. With the wafer thinner and diameter increasing, wafer compressive tensile strength becomes weaker, and more sensitive to external mechanical forces, which make the conventional diamond scribing technology cannot meet the challenges and requirements. It's urgent to find out a new processing technology. Laser processing has no mechanical force, it suitable for processing hard brittle materials. However, heat-affected zone (HAZ) is considered as a major drawback in the process of machining micro thermal material [2]. In fact, HAZ can be reduced or eliminated by using ultra short pulse laser. But the high cost of processing equipment, also such problems as low efficiency of ultra-short pulse laser limit their applications.

Liquid-assisted laser ablation process has become an alternative technique, which is able to cut and cool the workpiece simultaneously, and which can be used to decrease HAZ in the laser ablating materials such as silicon and other thermal sensitive materials [3–5]. Water is normally used since it is harmless, cheap and recyclable. Several ways were applied water to the laser machining process, such as under water laser [6,7], waterjet-assisted laser [8,9], waterjet-guided laser [10] and hybrid laser-waterjet machining [11]. These methods have been found to be some extent effective on reducing thermal damage and HAZ, and increasing material removal rate in the microfabrication of silicon. Wherein the performance of water-jet guided laser machining is the most outstanding, but its equipment is expensive and maintenance costs is high, which greatly limits its application. In recent years, scholars are competing research to replace the technology of water-jet guided laser processing. The advantages and disadvantages of water-assisted laser processing were further reviewed by Kruusing, and it concluded that laser machining process with different water-assisted way can be successfully used to cutting, etching, surface cleaning, and shock processing [3,4].

Although many researches focused on the laser cutting and drilling of silicon substrates underwater and with waterjet, some studies debated the mechanism of laser machining with different water-assisted way, little research on how the melt materials and water movement, and the process benefits have not been entirely indicated. Only fluid dynamics of water was studied to debris removal in laser scribing silicon underwater by Long [12]. In this study, fluid dynamics of water was discussed to debris removal in water-jet assisted laser machining of silicon, and it is applied to explain the process of material removal causing clean surfaces during waterjet-assisted laser etching, with smooth particle hydrodynamic (SPH) technique, which was used for the first time to study waterjet-assisted laser machining of silicon.

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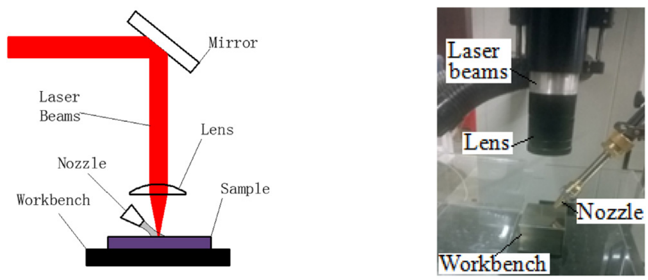

(a) Schematic (b) Physical map

Fig. 1. water-jet laser scribing experiment.

2. Experimental procedures

Fig. 1 shows the experimental setup of the water-jet laser scribing system, which includes a German original IPG fiber laser, a focal lens with a focal length of 85 mm and a sample container with water. The laser is a maximum laser power of 20 W, basic mode as laser output mode, optical quality M2 < 1.3, and electro-optic conversion efficiency of 35%. The specimen is silicon wafer of 6 N, which is ⟨100⟩, and has smooth surface and uniform thickness of 725 um. Water layer thickness is about 2.5 mm with a water-jet at the room temperature, which way can achieve good cooling and scrap removal effect, and reduce the attenuation of laser. The focused laser-beam with selected process parameters was focused on the specimen surface through the water layer. The focal plane position was a spot size of 100 um. A computer-aided design program was used to set the process parameters and scanning pattern. Experiments mainly studied the appearance and quality on the surface of silicon wafers after scribing in the air and with water-jet.

In this work, the effects of laser power and scanning pass number were investigated to understand the mechanism of water-jet laser machining. The laser machining in air was also made as a comparison. The study is to investigate the machining width, and the effect of water on machining quality including recast layers and cracks. Optical microscopy was employed to examine the morphology after laser machining, and scanning electron microscopy (SEM, FEI Quanta 200FEG) was used to capture the morphology of laser machined region.

3. Modeling approaches

An SPH model was also developed in this work to study the hydrodynamic behavior of interactions between water-jet and molten material during water-jet laser machining. Using the SPH method, the computational domain was divided into a set of discrete particles. These particles have a spatial distance, known as the smoothing length, over which their properties are smoothed by a kernel function. Different from the standard FE methods, SPH approximates physical quantities of each particle using the kernel function. The most attractive nature of SPH method is that it eliminates the need of computation termination due to the possible large element distortion inherent in Lagrangian formulation based FE methods [13]. Therefore, it is more suitable to simulating the fluid dynamics than the standard FE method.

The fluid in the SPH model was divided, and the properties of each of elements were associated with its center, which was then interpreted as a particle. A particle i has a mass m_i, position r_i, density ρ_i and velocity v_i. In SPH, the interpolated value of any field, A, at position r is approximated by [14]:

$$A\left(\vec{r}\right) = \sum_i m_i \frac{A_i}{\rho_i} W\left(\vec{r} - \vec{r}_i, h\right) \quad (1)$$

Where W is an interpolating kernel function, h is the interpolation length and the value of A at r_i is denoted by A_i. The sum is over all particles, i with a radius 2 h of r_i. $W\left(\vec{r}, h\right)$ is a spline based interpolation kernel function of radius 2 h, which is a C^2 function that approximates the shape of a Gaussian function and has a compact support. This allows smoothed approximations to the physical properties of the fluid to be calculated from the particle information. Thus, the particle approximation for each particle j can be approximated by summing the contributions of neighboring particles i as follows:

$$A\left(\vec{r}_j\right) = \sum_i m_i \frac{A_i}{\rho_i} W\left(\vec{r}_j - \vec{r}_i, h\right) \quad (2)$$

The finial discrete forms of governing equations (i.e. mass, momentum, and energy conservation equations) can be expressed as follows [15]:

$$\begin{cases} \dfrac{d\rho_j}{dt} = \rho_j \sum_i \dfrac{m_i}{\rho_i}\left(v_i^\alpha - v_j^\alpha\right) \dfrac{\partial W\left(x_j - x_i, h\right)}{\partial x_j^\alpha} \\ \dfrac{dv_j^\alpha}{dt} = -\sum_i m_i \left(\dfrac{\sigma_j^{\alpha\beta}}{\rho_j^2} + \dfrac{\sigma_i^{\alpha\beta}}{\rho_i^2}\right) \dfrac{\partial W\left(x_j - x_i, h\right)}{\partial x_j^\beta} \\ \dfrac{dE_j}{dt} = -\dfrac{\sigma_j^{\alpha\beta}}{\rho_j^2} \sum_i m_i \left(v_j^\alpha - v_i^\alpha\right) \dfrac{\partial W\left(x_j - x_i, h\right)}{\partial x_j^\beta} \end{cases} \quad (3)$$

where t donates the time, x is the spatial coordinate, vα is the velocity component, σαβ is the stress tensor component, E is the specific internal energy, and the subscripts α (α = 1, 2, 3) and β (β = 1, 2, 3) are the component indices. Simulation solutions were obtained by solving Eq. (3) in conjunction with equations of state, material models and initial and boundary conditions. This problem was solved by commercially available explicit CFD software AUTODYN (issued by ANSYS Inc.).

4. Results and discussion

4.1. Water jet effect

This experiment was divided into three groups, and the experimental parameters are as follows. In the first group, the laser output power is 16 W, scribing in the air; in the second group, the laser output power is 12 W, scribing with water-jet; in the third group, the laser output power is 16 W, scribing with water-jet. Based on the principle of control variables, repetition frequency is 100 kHz, pulse width is 25–50 ns, cutting speed is 10 mm/s, and scanning cycles is 4. When laser cuts in the air, sparks can be seen. When laser cuts underwater, a lot of bubbles come up in the cutting area. The results were respectively Fig. 2(a)–(c).

Fig. 2(a) shows the top-view of laser machining silicon in air at a power of 16 W. The discoloured recast layer on the surface indicated the high temperature during laser machining in air, which indicates that the thermal damages in processing region were serious during laser machining in air. Comparing with Fig. 2(a), when laser energy is 12 W with waterjet, Fig. 2(b) is smaller heat affected zone and finer deposited particles. there is a little bubble collapse traces, which indicates explosive boiling cannot ocuur with 12 w laser energy, and it is the main mechanism of molten material removal.

Under an exposure of silicon sample to laser energy of 16 W with waterjet, a significant change in the surface morphology was observed (shown as in Fig. 2(c)). Its etching is cleaner than in the air(shown as in Fig. 2(a)), less sediment is melt away because of more intense boiling. water-jet laser machining has been found to result in reducing silicon defects such as recast layer, dross and heat