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Ultrasonic-assisted underwater laser micromachining of silicon

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ABSTRACT

Underwater laser machining process can offer a clean cut with less thermal damage and material deposition on and nearby the cut region. However, the performance of this process is limited by the cut debris and bubble which can significantly disturb the laser beam during the ablation in water. In this study, the ultrasonic-assisted underwater laser ablation has been comprehensively examined to overcome the limitations of the existing process. The presented technique uses ultrasound to vibrate water while a workpiece is being ablated by a laser beam in water. This can atomize the bubble and energize the cut debris to be flushed away from the laser-ablated region. Silicon was selected as a work material in this study, where it was grooved by a nanosecond-pulse laser in water. The effects of ultrasonic parameters and water flow rate on the groove geometry and cut surface morphology were experimentally investigated and analyzed to understand the process performance. By using this technique, a clean and deep groove can be made on silicon wafer. The reactions between silicon–oxygen and silicon–carbon on the cut surface were also characterized and comparatively discussed with the other underwater laser ablation methods. According to the findings of this study, the ultrasonic-assisted underwater laser micromachining technique could be an alternative micromachining process to gain a higher material removal rate and a better cut surface quality than the other methods.

1. Introduction

Silicon is widely utilized as a substrate in electronic, photovoltaic and many high density system applications due to its excellent electrical and mechanical properties. In order to rapidly and accurately cut silicon substrate, laser is normally used since it can provide high photon energy and resolution for fine-scale ablation. Though a shorter wavelength laser such as ultraviolet lasers is preferred to yield a smaller cut feature on the substrate, the Nd:YAG laser whose wavelength is in the infrared spectrum is generally used due to its economical and efficient advantages. However, thermal damage caused by the infrared laser can crucially affect the functionality of silicon-based components. Some secondary post processes are therefore required to treat or recover the cut surface of silicon after machining. In general, recast layer and redeposition of molten material occurring on and nearby the laser-cut surface are undesirable and need to be washed away by chemical etching and/or ultrasonic cleaning processes. Moreover, the excessive heat conducting into the work material can cause heat-affected zone (HAZ) around the laser-ablated area, where the phase transformations of material and microcracks can be evident on and underneath the machined surface. These defects are discernable when the laser pulse duration of longer than some several picoseconds is used in the ablation process (Tangwarodomnukun et al., 2010). Under the long pulse irradiation, work material is removed via the photothermal mechanism where the melting and evaporation are responsible for the ablation and also the thermal damage.

In order to cut silicon without the presence of thermal damage, the ultra-short pulse lasers such as femtosecond lasers can be employed to directly break the atomic bonds of work material without the heat accumulation (Wan et al., 2011). This is because of the very short lasing time that is sufficient to rapidly vaporize rather than melt the work material. However, the high photon cost and low ablation rate of ultra-short pulse lasers are still unattractive for commercial usages. Liquid-assisted laser ablation process has become an alternative technique that is able to cut and cool the workpiece simultaneously. Water is normally used since it is cheap, harmless and recyclable. There are several methods for applying water into the laser machining process, e.g., water spray (Silvennoinen et al., 2013), underwater (Wee et al., 2011), overflow (Duangwas et al., 2014), thin water film (Tangwarodomnukun et al., 2015) and waterjet techniques (Tangwarodomnukun et al., 2012). The underwater laser ablation method is by far the simplest approach since it requires less transformation of the laser

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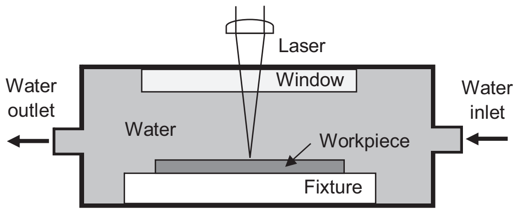

Fig. 1. Underwater laser machining in a closed chamber with water flow.

and optic systems. With regard to this technique, work material is ablated by a laser beam while it is submerged in water. The thickness of water layer covering on the workpiece surface can be varied from a few hundred microns to a few millimeters (Xu et al., 2014), depending on the laser wavelength and workpiece material. During the ablation process, water can cool down the workpiece temperature and also carry away the cut debris, thus reducing the size of HAZ and preventing the redeposition of removed material. Furthermore, a strong shock pressure induced by the plasma formation and collapse of cavitation bubble can mechanically assist the removal process in the confined volume of water. The shock wave in water and stress wave propagating in work material are found to be higher than that present in the ambient air ablation (Nguyen et al., 2014). Nevertheless, the shock wave traveling in water can generate waves at the top surface of water layer, in which the waves can dynamically alter the laser beam refraction and reflection. These optical disturbances are unacceptable for precise laser machining process. Typically, the underwater laser ablation is performed in still water or very slow water flow condition, where heat and material debris cannot be rapidly and directionally carried away from the workpiece. Hence, the uniform and flowing water layer should be applied to the underwater laser machining process for gaining a higher ablation performance.

The overflow-assisted underwater laser ablation method developed by Duangwas et al. (2014) can provide the uniform and flowing water layer over the workpiece surface during the laser machining process. In this method, workpiece is set up in a top-open container where water is pumped into the bottom side of the container, passes over the workpiece and then overflows from the container. As water continuously travels across the workpiece surface, the redeposition of cut material and HAZ can be reduced by using this method. However, the characteristics of overflowing water are dependent on the water flow rate, workpiece setup and container design. Under a proper overflow setup, a smooth water layer without waves at the air-water interface can be obtained. Another laser ablation technique performing in the flowing water condition was proposed by Tangwarodomnukun et al. (2015). Their technique incorporates a low-pressure waterjet to impinge the workpiece surface in order to form a circular thin water film covering the workpiece surface during the ablation. With this method, a higher material removal rate and a smaller HAZ can be achieved, compared to the laser ablation in still water. Dowding and Lawrence (2010) also noted that the thin laminar flow of water above the laser-ablated area can assist the ejection of work material during the machining. As the water film created by Tangwarodomnukun's technique is thin and uniform, the disturbance of water to the laser beam can be kept at minimum.

In order to control the water layer thickness as well as water flow characteristics, Charee et al. (2015) propose an underwater laser ablation method that the whole workpiece is submerged in a closed water chamber as shown in Fig. 1. A window made of borosilicate glass is applied to isolate air and water, making the clear-cut interface and controllable refraction of laser beam. Water is pumped into the chamber at one side and flows out from the opposite side to enable the directional flow. By using this technique, a cleaner and

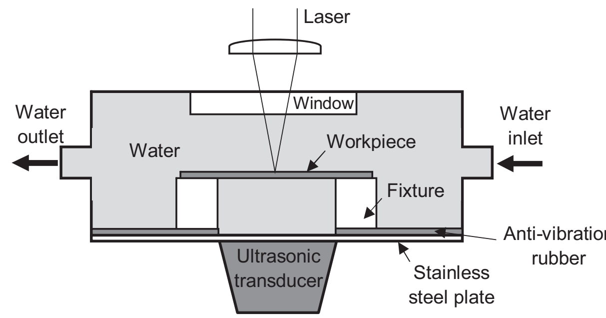

Fig. 2. Ultrasonic-assisted underwater laser ablation in a closed chamber with water flow.

Table 1
Process parameters considered in the experiments.

Process parameters	Level			
	1	2	3	4
Water flow rate (l/min)	4	6	8	10
Ultrasonic power (W)	20	30	40	50
Ultrasonic frequency (kHz)	20	40	60	
Laser traverse speed (mm/min)	50	200		
Laser pulse energy (mJ)	0.20	0.50		
Laser pulse frequency (kHz)	30			
Water layer thickness (mm)	5			

deeper groove can be made on silicon compared to the laser ablation in air and in still water conditions. However, bubbles resulted by the vaporization of water and workpiece material are found to be trapped in the chamber and adhere to the workpiece surface. The bubble diameter can be increased up to a few millimeters, and it can optically change the focal position of incident laser on the workpiece surface. In order to remedy this side effect, the bubble should be atomized and forcefully flushed away by water rather than adhere to the workpiece.

In general, the ultrasound whose frequency of above 20 kHz can be used to remove particles and debris material form the workpiece surface after machining (Fuchs, 1992). This is due to the fact that the ultrasound can induce the kinematic energy to the particles for the purpose of removal. One of the first reports on the ultrasonic-assisted laser machining process was proposed by Mori and Kumehara (1976), presenting that the material debris and slag can be quickly decomposed and removed under the ultrasonic condition in ambient air. Chiu et al. (2010) applied the ultrasound to aid the laser drilling process where workpiece is ultrasonically vibrated along the laser beam direction. The results show that the ultrasound can increase the hole depth and decrease the surface roughness including the surface oxidation, HAZ and recast layer. With regard to the decreased HAZ, Kang et al. (2012) noted that when workpiece is ultrasonically moved during the laser ablation in ambient air, the near-field surface cooling of workpiece can be enhanced and then causes less amount of heat conducting toward the bulk material.

Though the ultrasonic-assisted laser machining process performed in the ambient air has been examined by many studies, there is very little discussion on the ultrasonic-assisted underwater laser ablation. An ultrasound-assisted underwater laser machining process was proposed by Wu (2014) and its investigation was done by Liu et al. (2014). They found that a clean and deep hole can be made by using the 532-nm laser in water with the ultrasonic frequency of 20 kHz. This can be remarked that a greater machining performance than that provided by the other laser ablation techniques is plausible by integrating the ultrasound with the laser ablation in water. Since the ultrasonic wave can generate the high frequency impulses in water, the bubble generated during the laser ablation in water could be broken up into a smaller size. This could