Optics and Laser Technology 100 (2018) 230–243

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Dynamic features of bubble induced by a nanosecond pulse laser in still and flowing water

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ARTICLE INFO

Article history:
Received 4 August 2017
Received in revised form 11 September 2017
Accepted 21 October 2017

Keywords:
Laser
Water
Flow
Silicon
Ablation
Bubble

ABSTRACT

Underwater laser ablation techniques have been developed and employed to synthesis nanoparticles, to texture workpiece surface and to assist the material removal in laser machining process. However, the understanding of laser-material-water interactions, bubble formation and effects of water flow on ablation performance has still been very limited. This paper thus aims at exploring the formation and collapse of bubbles during the laser ablation of silicon in water. The effects of water flow rate on bubble formation and its consequences to the laser disturbance and cut features obtained in silicon were observed by using a high speed camera. A nanosecond pulse laser emitting the laser pulse energy of 0.2–0.5 mJ was employed in the experiment. The results showed that the bubble size was found to increase with the laser pulse energy. The use of high water flow rate can importantly facilitate the ejection of ablated particles from the workpiece surface, hence resulting in less deposition to the work surface and minimizing any disturbance to the laser beam during the ablation in water. Furthermore, a clean micro-groove in silicon wafer can successfully be produced when the process was performed in the high water flow rate condition. The findings of this study could provide an essential guideline for process selection, control and improvement in the laser micro-/submicro-fabrication using the underwater technique.

1. Introduction

Several liquid-assisted laser ablation techniques have been developed and employed to synthesis nanoparticles [1–4], to change surface properties of workpiece through laser shock processing [5] and to remove work materials with less thermal damage than usually found in the typical laser machining processes in ambient air [6–8]. Though many types of liquid can be used to assist the ablation process, a famous liquid mostly employed is water. This is due to some remarkable characteristics of water that can conduct more heat from work materials being ablated by a laser, be transparent with less light absorption in the spectrum of industrial lasers, and be of recyclability without any special requirements. The contributions of water in laser ablation are mostly accounted for the material removal processes; e.g. drilling [7,9,10], grooving [11], cutting [12] and milling [13] operations.

Water can be applied to the laser machining processes in various methods such as submerging the whole workpiece in water while performing the laser ablation [12], creating a water layer on the workpiece surface [11] or using a waterjet to assist the laser ablation as a hybrid process [14]. Despite using different water applying methods, the common roles of water in the laser machining processes are (1) to reduce heat accumulation in work materials during the ablation, (2) to prevent the deposition of hot cut debris potentially landing on the workpiece surface and (3) to facilitate the material removal through the mechanical shock induced by the optical breakdown in water. A small heat-affected zone, clean cut surface and great volume of material removed can be expected when water is employed to assist the laser machining of metals [6,7,15], polymers [16], ceramics [17–19] and semiconductor materials [9,10]. However, laser beam scattering and beam blockage due to the bubble formation in water are the negative effects induced by the hydrodynamics of water, and these adversely affect the laser ablation performance and quality of cut features obtained.

When a material is irradiated by a laser beam in water, the material as well as water surrounding the ablation region is rapidly vaporized. This in turn forms a plasma plume enveloped in an expanding cavitation bubble on the laser irradiated area [20–22]. The initial bubble usually demonstrates a well-defined and smooth boundary during its growth and shrinkage [23]. The size of cavitation bubble depends on many factors. Martí-López et al. [5] found that an increase in water layer thickness decreases the size of

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https://doi.org/10.1016/j.optlastec.2017.10.019
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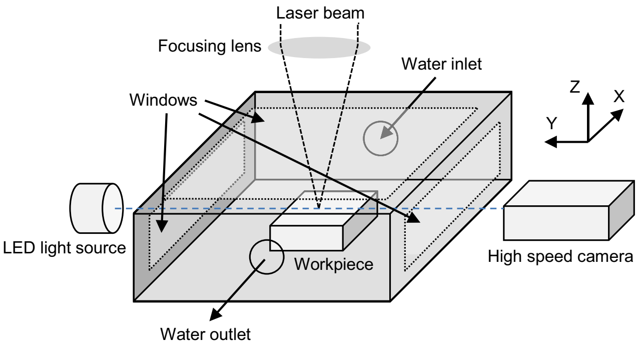

Fig. 1. Underwater laser ablation.

bubbles. Water temperature [24], additives in water or liquid properties [25] and surface characteristics of workpiece [26] can also affect the bubble size as well as the focal position of laser beam with respect to the workpiece surface [27].

When a laser beam strikes the workpiece surface to cause the bubble formation, a shock pressure is instantly created and it radially propagates to surrounding water and work material through shock wave and stress wave. The shock wave in water can travel to the air-water interface above the workpiece surface and then rebound back to the workpiece. The bubble expansion and decay can cause water wave at the interface and dynamically change the refracted laser beam in water, thus altering the location of laser beam during the ablation so as the accuracy of machining process. The size of cavitation bubble importantly affects the magnitude of shock waves and stress waves produced. Zhang et al. [28] noted that the ablated surface morphology and process performance are subjected to the bubble size and laser pulse repetition rate used in the underwater laser machining process. The cavitation bubble is found to increase with time until reaching its maximum size. The change of bubble size can dynamically scatter the incident laser beam and also change the position of laser striking the workpiece surface [28]. When the maximum size of bubble is reached, the bubble collapses and releases another shock pressure to the surroundings [20–22,24,25]. Bai et al. [29] found that a micro-jet produced during the collapse of bubble impinges toward the workpiece surface as a mechanical shock. This shock pressure can expel some molten elements from the ablation zone, hence increasing the material removal rate. After the first bubble collapsing, the subsequent bubbles created by the following laser pulses undergo expansion and collapse with the repeated behaviors.

Though many past studies can elucidate the understanding of bubble formation and its effects on the laser material processing in liquid environment, the formation and characteristics of cavitation bubble induced by laser ablation in water as well as other liquids have only been investigated in a few first laser pulses. The interactions between laser, work material and water taking place in a longer time span with several ten thousand laser pulses per second have not been presented yet. Furthermore, the effects of water flow on the bubble formation and laser-ablated surface morphology have not been realized ever before. Hence, this paper is for the first time to reveal the laser-material-water interactions with an extended period of time during the laser ablation process in water. The findings of this work would essentially provide better understanding of laser-material-water interactions and ablation performance of laser material processing in water.

2. Materials and methods

A nanosecond pulse laser providing the wavelength of 1064 nm and pulse duration of 120 ns was used in this study. The maximum

Table 1
Process parameters considered in the experiments.

Process parameters	Level			
	1	2	3	4
Laser pulse energy (mJ)	0.2	0.3	0.4	0.5
Water flow rate (l/min)	4	6	8	10
Laser traverse speed (mm/min)	50			
Laser pulse repetition rate (kHz)	30			
Water layer thickness (mm)	5			

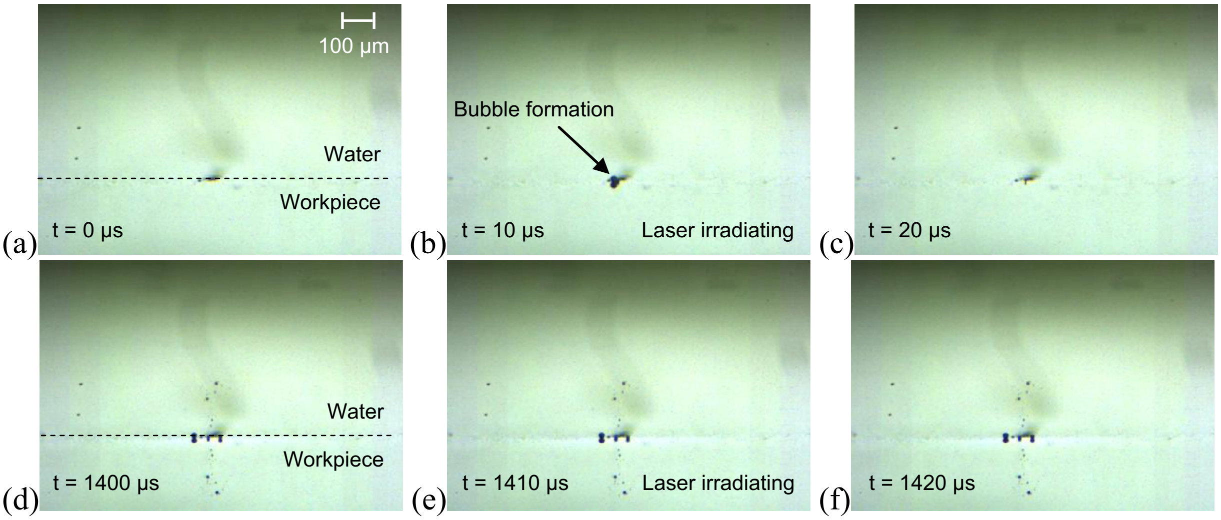

Fig. 2. Bubble formation induced by the ns-pulse laser with the pulse energy of 0.2 mJ in still water.