Applied Surface Science 257 (2011) 3677–3681

Contents lists available at ScienceDirect

Applied Surface Science

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

The research on mechanical effect etching Si in pulsed laser micromaching under water☆

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ARTICLE INFO

Article history:
Received 13 August 2010
Received in revised form
16 November 2010
Accepted 16 November 2010
Available online 24 November 2010

Keywords:
Laser technique
Mechanical effect
Laser
Etching
Silicon

ABSTRACT

To explore further the influencing of mechanical effects on laser machining in the liquid, in the process of great-energy and short-pulsed laser irradiating matter in the liquid, the experiments of 248 nm laser etching *n*-Si under water were carried out. The removal mechanism of brittle material etched by mechanical effects, which is induced during high-energy and short-pulsed laser machining in the liquid, was discussed. In the paper, the approximate mechanics model of indentation fracture was used to analyze the mechanical effects for removing brittle materials of silicon when laser machining in the liquid. Based on this, a theoretical model of material removal rate was proposed; the experiment of laser machining under water was adopted to validate the model. The experimental results indicate that the removal rate of brittle material caused by shock forces is relatively great.

1. Introduction

The effect of laser machining depends primarily on the heat effects and mechanical effects caused by laser interacting with the target. The mechanism is mainly mechanical effects during short-pulse and high-energy laser interacting with material [1,2]. Moreover, the mechanical effects when laser machining in the liquid are particularly notable.

Laser processing is usually carried out in air; the corresponding research theory has been more mature. However, laser processing in the liquid is a new problem. In a gas environment, when high-energy and high-intensity laser irradiating the surface of solid target, there will be an optical breakdown at the target surface, and plasma and shock wave are formed [3]. When the target immersed in a liquid medium, the incompressible liquid limits laser plasma to expanse externally and then there increases the recoil pressure caused by the shock wave of plasma to the target. In addition, in the process of high-energy and short-pulsed laser machining material in the liquid, when the temperature of heating wall is rapidly ultra-high overheating, there will continue to emerge prominently new bubble embryos. When the vacuoles collapse near a solid wall, the gradients of stress on the bubble surface will form a liquid jet of high-speed to the target. This is a unique phenomenon of cavitations when laser processing in the liquid [4,5]. Many scholars have had a wide range and in-depth researches on the laser bubble, and have made great progress [6,7]. There exist these particular phenomena, which lead to very significant mechanical effects when high-energy and short-pulsed laser interacting with these materials in the liquid. Moreover, in high-energy and pulsed laser machining the target in a liquid, the significant mechanical effects were firstly reported by Chen et al. and Xu et al. [8,9]. The mechanical effects have a large influence on the etching role. However, the research in this area is still in the initial stage, and the relevant report is few.

The purpose of this paper is to explore the mechanical effects of influencing on the laser machining in the liquid (such as laser electrochemical processing). When a laser of high-power density irradiating material in a liquid, the experiments of laser etching the target in the liquid were carried out with the power density of 10^9 W/cm^2 and pulsed laser of 248 nm focusing on *n*-Si surface under water. Mechanical effects, which are caused by high-energy and short-pulsed laser machining in the liquid, influencing on the removal mechanism of brittle materials were discussed in details. Based on this,, the approximate mechanics model of indentation fracture was used to analyze the mechanical effects for removing brittle materials of silicon, and a mathematical model of material removal rate was set up. In the end, the model was inspected and

☆ This project was funded by National Natural Science Foundation of China (Grant No. 51065007, No. 50975113, No. 60866002) and the director Fund of Guangxi Manufacturing Systems and Advanced Manufacturing Technology Laboratory (Grant No. 0842006_030_Z).

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doi:10.1016/j.apsusc.2010.11.105

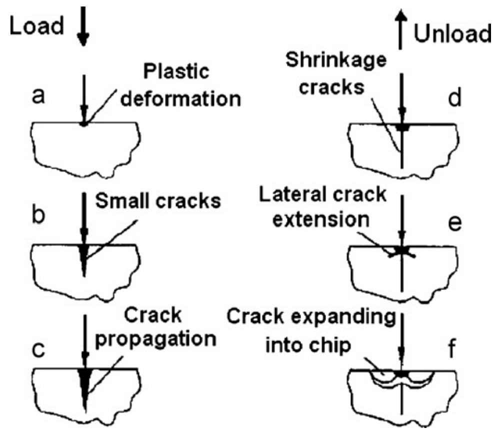

Fig. 1. Indenting process of diamond indenter on the brittle material surface.

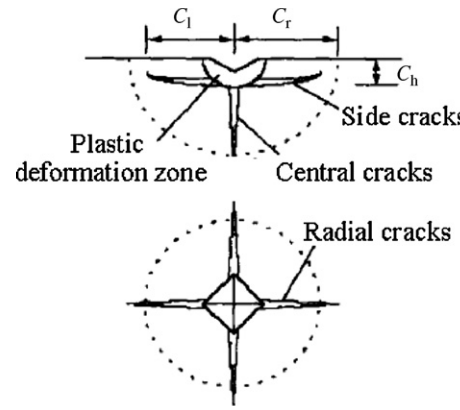

Fig. 2. Crack size induced by pressure.

verified by the experimental results of laser machining a target under water.

2. The removal mechanism of impact forces to brittle materials

The impact mechanisms of hard and brittle materials are mostly approximate to the mechanics model of indentation fracture in the research. The mechanics of indentation fracture is combined with the basic model of indentation fracture and Griffith–Irwin fracture mechanics. Comparing the interaction of the particle and workpiece to the local indentation, the crack nucleation, formation and expansion, distribution of complex elastic–plastic stress, and stress and energy conditions of ultimately leading to fracture were researched [10]. Since the micro-cracking process of sharp indentation was reported in 1975, the micro-fracture mechanics of indentation on hard and brittle materials have developed rapidly, and the researches on majority processes of indentation are developed based on this mechanics [11]. In the approximate model on mechanics of indentation fracture, the interaction of the abrasive and workpiece in the process of impacting hard and brittle materials is regarded as the phenomenon of small-scale indentation. When diamond indenter of Vickers pressing on the surface of hard and brittle materials in mechanics of fracture, the main process on conformation of indentation crack is shown in Fig. 1 [12]. First, when the pressure head presses into the material surface, the compressive stress will make the specimen below the pressure head occurring non-elastic flow, and result in a region of plastic deformation, as shown in Fig. 1(a). To a hard and brittle material, there is a critical load of F_c, which determines the way of material deformation. When a pressure value of F on the material surface is more than the critical load F_c of material, there will be a central crack just below the pressure. The intermediary cracks also grow with the load increasing, as Fig. 1(b) and (c) displays. When the load unloads after the pressure reaching a critical load of pressure, the intermediary cracks will begin to close but not heal, and there will be a crack, as can be noted in Fig. 1(d). Further unloading, due to no match of elastic–plastic stress in the contact area, a tensile stress is superimposed in the stress field, and then there generates a series of transverse cracks with expansion to the side. Finally, when the lateral cracks continue to expand, there generate simultaneously radial cracks, side cracks and central cracks, which are respectively caused by the pressure on the surface, the side and the central parts of brittle materials, as shown in Fig. 1(e) and (f). When the crack extends to the workpiece surface or two adjacent cracks of indentation meet, it will generate debris and the material is removed.

Simultaneously, the mechanics model of indentation fracture has been applied to study the mechanism of machining hard and brittle materials when existing the impact action in various processes. Buijs et al. [13] used the theory of indentation fracture to explain the glass surface for polishing of abrasives removal. It is proposed by Wang that the wallop impacting workpiece in the ultrasonic machining process is in a manner and effect similar to the pressure head acting brittle materials in the experiments of indentation hardness [14]. The material removal in ultrasonic processing depends on the part and instantaneous impact of teeny abrasive. In the process of abrasive waterjet, the impact process of abrasive particles is similar to the process of the indenter pressing into material. Therefore, the mechanics model of indentation fracture is used to study the materials removal model for process of abrasive waterjet [15]. The mechanism for the hydrodynamic suspension ultra-smooth machining silicon was investigated using the mechanics model of indentation fracture by Cao et al. [16].

Laser machining in the solution is a complex dynamic process. In high-energy and short-pulsed laser machining materials in the liquid, the materials removal by the mechanical effects is mainly local impact. Local impact vertically impacts to the material surface, and crack growth of material leads to brittle fracture and removes material. The process is similar to the process of indenter pressing into the surface in mechanics of indentation fracture. To analyze the mechanism of material removal, the fracture mechanism of brittle materials under the impact load was first analyzed. Therefore, in this study, the approximate mechanics model of indentation fracture was used to analyze the mechanical effects for removing brittle materials of silicon during laser machining in the liquid.

3. Removal model building

In high-energy and pulsed laser machining in the liquid, the following model of materials removal rate for mechanical effects on brittle materials is founded on basis of the above-mentioned principle [17].

3.1. The calculation of crack size

When F is greater than or equal to F_c, there generates a crack, as shown in Fig. 2. The length definition of radial cracks and side cracks are respectively C_r and C_l, then:

$$C_r = \xi_1 \sqrt{F}\,\sqrt[4]{H}\,\sqrt[3]{K_{IC}} \tag{1}$$

$$C_l = \xi_2 \left(\frac{F}{K_{IC}}\right)^{3/4} \tag{2}$$