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Study on immersion waterjet assisted laser micromachining process

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ABSTRACT

The heat affected zone (HAZ), recast layer, and taper angle are the issues remained to be addressed in laser micromachining. In immersion waterjet assisted laser micromachining (IWALM) the waterjet flushes the ablated materials, plasma, and micro bubbles away from the machining area at laser pulse interval. A higher machining resolution could be obtained by reducing the laser beam through focusing system. This paper studied the mechanisms of IWALM and the effects of microbubbles explosion on the workpiece surface roughness around the entrance of machining area. With the developed experimental setup, the influences of the laser power, waterjet flow speed, and workpiece-nozzle gap were studied on the machining efficiency, taper angle, while machining microhole with diameter 0.5 mm by scanning the laser beam within waterjet diameter. In particular experimental conditions, the machining efficiency of IWALM was larger than that of laser micromachining in the air, while the workpiece thickness was smaller than 0.5 mm. Microholes with reduced HAZ and free of recast layer were fabricated by IWALM. The taper angle of the microholes processed by IWALM was 376% smaller than that by Laser micromachining in the air. Furthermore, the mechanisms of the formation of micro-pits during IWALM around the machining area were discussed, considering the explosions of micro bubbles near the workpiece surface due to the pressure difference. Experimental results indicated that a higher waterjet flow speed and smaller nozzle-workpiece gap, laser power could improve the surface quality in close to the machining area.

1. Introduction

Laser micromachining is increasingly applied to fabricate micro components and structures widely used in aerospace, biomedical, microelectronics, and micro electro mechanical systems (MEMS), etc. (Mishra and Yadava, 2015). Laser micromachining provides an efficient, high accuracy and feasibility method for micromachining, with precision control of laser energy input and flexibility on laser beam transmission. In Laser micromachining, materials are mainly removed by vaporization, in which materials adjacent to the laser-materials interaction area absorb a portion of heat. The heat stresses and heat affected zone (HAZ) usually follows the high ablation rates of laser micromachining (Stephen, 2011). However, to guarantee the performance and lifespan of microcomponents processed by Laser micromachining, the surface quality including HAZ and recast layer should be considered. Moreover, the dust is produced during laser micromachining in the air, which should be avoided in case of air pollution.

A number of efforts have been endeavored by researchers to improve the surface quality of the microstructures processed by laser micromachining, and ultrafast pulse lasers (Cheng et al., 2013), excimer laser (Desbiens and Masson, 2007), water assisted laser micromachining (Ren et al., 2005), laser microjet (Perrottet et al., 2005), and laser hybrid micromachining (Mishra and Yadava, 2015) et al. have been proposed for micromachining. These methods have been compared regarding HAZ, machinable depth, efficiency, cost, dust pollution, and reliability, as shown in Table 1.

In the past two decades, ultrafast lasers including femtosecond and picosecond lasers have been employed for high accuracy and high-resolution micromachining, due to the nonlinear absorption effects induced by ultrashort timescale and ultrahigh intensity (Nolte et al., 1997). Huang et al. (2017) fabricated three-dimensional (3D) microstructures in bulk materials by using femtosecond pulsed lasers in micromachining. Meijer et al. (2002) studied the mechanisms of laser micromachining by ultrashort laser pulses and indicated that shorter pulses could reduce HAZ of the processed materials. Ito et al. (2018) revealed the formation of microscopic damage formation was induced by the stress wave during the femtosecond laser drilling process. Ultrafast pulse laser has been used for 3D microfabrication in various materials, such as metals, polymers, ceramics, composites materials, etc. However, the ultrafast laser systems are always expensive, and the materials removal rate (MRR) is generally lower than that of laser processing with longer pulse duration with increasing machining depth

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Table 1
Characteristics of various laser micromachining methods.

Type	HAZ	Machinable depth	Efficiency	Cost	Dust pollution	Reliability
Ultrashort laser pulse micromachining	Low	Low	High	High	High	High
Excimer laser micromachining	Low	Low	Medium	Medium	High	Medium
Water assisted laser micromachining	Low	Medium	Medium	Low	Low	Medium
Laser microjet	Low	Medium	Medium	High	Low	Low
Liquid core waveguide laser micromachining	Low	High	Medium	Medium	Low	Low

(Li and Achara, 2004). Excimer laser ablation is generally employed for lithography used in microelectronics, as studied by Hind (2001). With excimer laser, a smaller spot size could be imaged by reduced diffraction, and less thermal influence or melting occurs due to the mechanism of photoablation (Ready, 2001). Nevertheless, because the ultraviolet laser could be strongly absorbed by most materials, the efficiency of excimer laser ablation is limited. Also, the machining depth of the microstructures is smaller than that processed by other methods.

Further, water assisted laser micromachining was developed to reduce the heat effect, taking advantage of the cooling effect of the water. Zhao and Shin (2011) found that the laser drilling in water could generate high aspect ratio and cleaner channels at low pulse energy. Tangwarodomnukun et al. (2014) used an off-axial water jet to expel the laser-softened elemental materials to decrease thermal damages and increase MRR. Lu et al. (2004) studied the mechanisms of laser drilling in liquid and proved that both the efficiency and surface quality of laser processing in the surrounding water could be improved compared with that in the air. Yan et al. (2011) explained the effect of water on crack resistance and debris removal during underwater laser beam micromachining (LBMM) and found that the water layer thickness was an essential factor for the kerf width and depth. Bao et al. (2016) employed Smooth Particle Hydrodynamic (SPH) modeling technique to understand the effect of water and waterjet on debris removal during waterjet laser machining. Tangwarodomnukun et al. (2015) proposed nanosecond-pulse LBMM under a thin and flowing water layer, and experimentally investigated the effects of laser power, traverse speed, pulse frequency, and waterjet flow rate, on groove geometry and heat-affected zone. Madhukar et al. (2016) found that the amount of laser energy required to remove unit volume of material was more in waterjet assisted laser cutting due to the energy losses associated with absorption and scattering in liquid. It was also demonstrated that waterjet assisted LBMM could produce microstructures with lesser microcracks, spatter, and thermal damage. López et al. (2016) proposed droplet assisted laser micromachining in which impulse shock pressure arisen from explosive vaporization of the droplet inside the laser irradiation zone could improve the materials removal rate by 75% and reduce the spatter redeposit by 71%, compared to dry nanosecond laser micromachining. Cavitation bubbles were formed while nanosecond lasers were applied to the materials in water, as studies from Jiang et al. (2017). Chen et al. (2017) utilized the shock wave induced by the explosion of cavitation bubbles for punch forming of the aluminum foil. Zhai et al. (2017) concluded that a proper application of plasma shock wave in liquid could improve the roughness of the machined area and avoid splashes deposits at the hole entrance. Feng et al. (2018) modeled and investigated the material removal mechanisms in the hybrid laser-waterjet micromachining, and noted that the machined surface texture was characterized as a feature of plastic slip without recast layer. Mistry and James (2018) revealed that the width and the depth of the HAZ decreased significantly with water film thickness of 0.5 mm and higher in liquid assisted laser beam machining. Thus, water assisted laser micromachining could improve the surface quality of the processed microstructures. However, the machining efficiency and depth is limited by the difficulties in the diffusion of the cavitation bubbles and melts out of the machining area. Moreover, the thickness of the liquid layer is difficult to be controlled, and the micromachining efficiency is limited by the moving speed of conventional moving platform. The mechanisms of water assisted laser micromachining and the effects of cavitation bubbles on the machining area should be further studied.

Laser microjet technology, developed by Richerzhagen (1999), adoptedthe the coaxial micro water jet as the medium for guiding laser beam with internal total reflection. This process enables micro drilling and cutting of various materials free of thermal damage, deposition, and oxidation. Sun et al. (2018) concluded that the HAZ is reduced compared with the conventional laser beam machining, but the machining efficiency was also dropped. Zhang (2006) invented a liquid core waveguide photon energy material processing technology, in which a double-layered tube guides the laser beam. It could penetrate into the workpiece materials and thus machine high-depth microholes. However, both laser microjet and liquid core waveguide method machining resolution are restricted by the diameter of micro waterjet and liquid core waveguide. Moreover, the high-power laser could not be employed due to the vulnerability of the micronozzle and microtube of the diameter smaller than several dozen micrometers.

In this work, microhole drilling with immersion waterjet assisted laser micromachining (IWALM) is proposed for improving the machining efficiency, the reliability of water assisted laser micromachining, and avoid dust pollution to the air. A higher machining resolution could be obtained by reducing the laser beam through focusing system. It employs a high speed and a relatively large diameter waterjet to expel the heat, cavitation bubbles and ablated materials out of the machining area. The laser is focused on the workpiece that is immersed in the water. This paper mainly focuses on the study of machining mechanisms of IWALM and the effects of waterjet parameters on the machining efficiency, thermal effects, and machining precision. Further, the influences of cavitation bubbles explosion around the entrance of the machining area are researched experimentally.

2. Mechanisms of IWALM

As shown in Fig. 1, in IWALM a nanosecond pulse laser with wavelength of 527 nm is focused on the workpiece through a focusing len, and a high-speed waterjet is impinged on the workpiece surface machining area in perpendicular direction. The workpiece is immersed in the water to minimize the heat effect during laser micromachining. The laser beam scans on the workpiece machining area within the radial range of the waterjet diameter. Thus, microstructures with a particular profile, such as microholes, microgrooves, and micro slits, could be processed by controlling the scanning paths of the laser beam on the workpiece via galvanometer optical scanner. The scanning speed of the galvanometer optical scanner could be far higher than that of the conventional mechanical moving platform. Compared with laser microjet technology, a relatively large diameter nozzle could be employed for obtaining a larger diameter waterjet ($\geq$ 1 mm), and the laser beam could move in the waterjet with the controlled trajectory. Thus, the stability could be improved in case of the contact between nozzle wall and laser beam, which could destroy the nozzle side wall. Also, the machining resolution could be improved by decreasing the diameter of the laser beam to several micrometers, utilizing the focusing len of smaller focal length. By IWALM, heat sensitive materials could be processed with a high resolution, and without dust pollution to the air.

In nanosecond pulse laser micromachining, the recoil pressure generated by plasma and vapor expulse the ablated materials out of the