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Droplet assisted laser micromachining of hard ceramics

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ABSTRACT

Hard ceramic materials like tungsten carbide (WC) are extensively used in high value manufacturing, and micromachining of these materials with sufficient quality is essential to exploit its full potential. A new micro-machining technique called droplet assisted laser micromachining (DALM) was proposed and demonstrated as an alternative to the existing nanosecond (ns) dry pulse laser ablation (PLA). DALM involves injecting liquid micro-droplets at specific frequency during the nanosecond laser micromachining to create impulse shock pressure inside the laser irradiation zone. The impulse shock pressure is generated due to the explosive vaporisation of the droplet, during its interaction with high temperature laser irradiation zone. In this paper, the DALM uses a nanosecond pulsed Nd:YAG laser to machine tungsten carbide substrate. The results suggest that the impulse shock pressure generated during the DALM process can transform the melt ejection mechanism of the ns laser micromachining process. The change in ejection mechanism results in a 75% increase in material removal rate and 71% reduction in the spatter redeposited compared to conventional dry ns laser micromachining.

1. Introduction

Hard, advanced ceramic materials such as tungsten carbide (WC) have excellent mechanical and thermal properties, including hardness, wear resistance and retention of strength at elevated temperatures, making them suitable for a wide range of applications from aerospace to tooling. It is these properties that make micromachining of WC challenging by conventional means and machining these materials is essential to fully realise their potential. Across a number of industries there is an increasing demand for components with both micro-scale features and the excellent properties afforded by modern day advanced ceramics. New fabrication techniques have been developed to improve micromachining, including ion-beam, electrical discharge and laser micromachining [1].

Micromachining using short (microsecond-nanosecond) and ultra-short (picosecond-femtosecond) pulsed lasers is becoming an important process to machine hard materials like WC. Dry pulse laser ablation (PLA) by nanosecond lasers is extensively used across range of industries [2], however significant spatter re-deposition and thermal damage was reported [3] at higher material removal rate (MRR). Ultrashort pulse laser machining using picosecond (ps) and femtosecond (fs) lasers is portrayed as an alternative to ns laser machining, however high frequency ultrashort pulse laser machining cannot be used for thick materials due to plasma shielding effect [4], its MRR is typically less than ns machining and is currently used mostly for micromachining of thin materials [4]. Moreover the cost of ultrashort pulse lasers is of an order of magnitude higher than similar average powered ns lasers.

The mechanism of dry ns PLA involves substrate absorption of laser fluence followed by melt pool formation, partial vaporisation and ejection of melt pool by vapour pressure. In dry PLA only part of the melted material is vaporised or ejected and the rest resolidifies inside the laser irradiated zone as a recast layer. Also, a considerable quantity of the ejected material is redeposited as dross (or spatter), around the edge of the micromachined region (over the material surface) [5–7]. In typical ns laser micromachining the material removal rate is inverse proportional to the micromachining quality [8].

Synova has developed a micro-jet based laser drilling, in which, a ns Nd:YAG laser beam travels co-axially to a water jet [9]. The water jet helps to address the residual heat build-up during conventional nanosecond laser processing. This process produces good quality micromachining [10]. However, the micro-jet process is slower than dry ns PLA, cannot be used with all laser wavelength, cannot be used with high powers lasers and has disadvantage of being a wet process. A recent development in ns PLA is the underwater laser process, in which the substrate is submerged in a liquid medium [3]. Studies have shown that the underwater laser pro-

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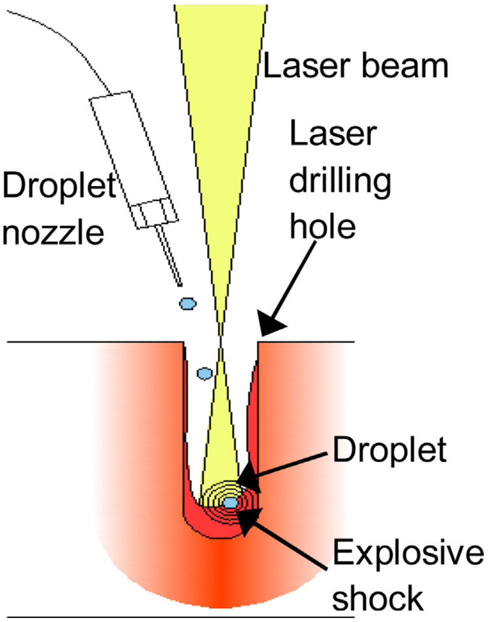

Fig. 1. Schematic of DALM setup.

cess helps to control the residual heating and decrease the spatter deposition; however maintaining a uniform water layer thickness is a challenging and the process has the practical disadvantages of being a wet process.

This paper reports preliminary investigations into the droplet assisted laser micromachining (DALM) process for micromachining of WC material. The droplet assisted laser micromachining process exploits the combined potential of conventional ns laser processing, shock processing [9] and wet processing [3,10], through the use of fine liquid droplets of size 150 μm. Though, this paper focuses on machining of WC ceramics, the DALM process should be applicable to most metals, alloys and ceramics.

2. Experimental procedure

Tungsten carbide blocks (P10 grade) of dimension 50 mm × 40 mm × 10 mm were used as test samples. The P10 grade is the standard tool material used for finish pass machining of steel components. Laser micromachining was performed with and without liquid droplets, so as to evaluate the performance of DALM based micromachining compared to conventional dry PLA process [4]. A schematic diagram of the DALM setup is shown in Fig. 1. Compared to the conventional dry PLA experimental setup, the DALM based micromachining system has an additional liquid dispenser (micro-dispenser) capable of delivering a controlled volume of liquid at a specific frequency and time. The micro-dispenser was used to inject the liquid droplets over the laser irradiation zone (to induce shock and remove the dross and recast layer). The frequency of the laser beam and micro-dispenser were synchronised to work in sequence. The laser source used for this experiments is a LITRON frequency tripled Q-switched Nd:YAG laser with a wavelength of 355 nm, maximum pulse frequency of 10 Hz and a pulse duration of 8 ns. Water was used as the liquid medium. A three axis linear stage was used to move the sample relative to the droplet/laser focus. All experiments were performed under ambient conditions without the influence of any assist gas [3,12].

The droplet dispenser has a nozzle exit diameter of 150 μm and was operated at 0.4 bar water pressure and 30 ms nozzle on-time. For all experiments the diameter of the droplet were maintained at 150 μm which was optimal for the droplet dispenser and the frequency was chosen to match the maximum laser pulse frequency of 10 Hz. A strobe light along with a CCD camera was used to identify the path of the droplets, and to ensure that the droplet hits the laser irradiated zone. The initial laser micromachining experiments were performed both with and without droplets to choose the range of the experimental parameters. The laser fluence was varied from 0.1 to 6 J/cm^2 and the number of pulses per position was varied from 25 to 500, to understand the significance of DALM and the conventional dry PLA process. All experiments were performed with a stationary laser beam and a stationary work piece. Finally, the laser micromachined samples were analysed using optical microscopy, scanning electron microscopy (SEM), elemental energy dispersive spectroscopy (EDX) and a white light interferometer.

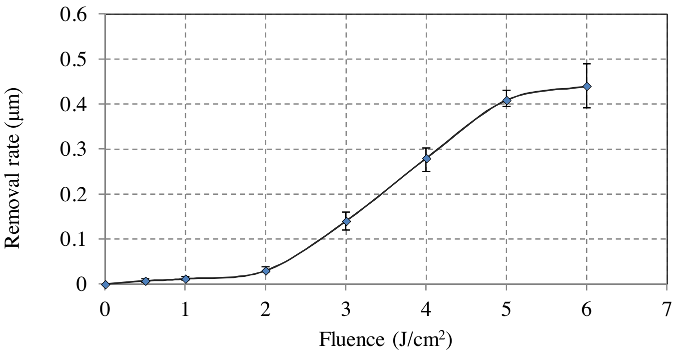

Fig. 2. Graph showing effect of laser fluence on removal rate for DALM (No of laser and droplet pulse = 250; Laser frequency = 10 Hz; Droplet frequency = 10 Hz).

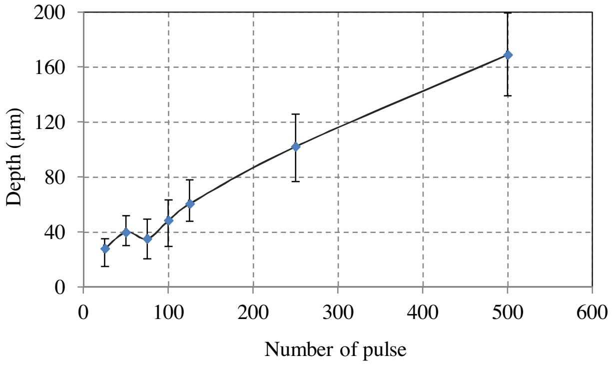

Fig. 3. Graph showing effect of number of pulse on the depth for DALM (Laser fluence = 5 J/cm^2; Frequency = 10 Hz).

3. Results

The ablation rate of DALM based laser micromachining process, performed on a flat WC plate is shown in Fig. 2. As can be seen from the figure, a positive correlation was observed with increase in fluence; however the variance is amplified at the high fluence range of ~2–5 J/cm^2. As elucidated from the figure, the ablation threshold of the WC with DALM based laser micromachining process is close to 2 J/cm^2. A fluence of 5 J/cm^2 was chosen for further experiments due to its high material removal rate compare to the threshold ablation fluence. Also noticed from the figure is that the ablation rate becomes saturated above 5 J/cm^2, which is likely to be due to plasma shielding effects. The ablation trend of DALM based laser micromachining is similar to the one observed with dry PLA process, however, the magnitude of removal rate is significantly higher in DALM based process [4,6,11].

Fig. 3 shows the effect of laser pulse per position on ablation depth. As can be seen from the figure a strong linear relationship

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