Journal of Materials Processing Technology 232 (2016) 52–62

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Evolution of geometric and quality features during ultrasonic vibration-assisted continuous wave laser surface drilling

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ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form 8 January 2016
Accepted 26 January 2016
Available online 29 January 2016

Keywords:
Ultrasonic vibrations
Laser processing
Laser drilling
Melt expulsion
Material removal

ABSTRACT

Recently, the processes involving simultaneous application of ultrasonic vibrations during conventional materials processing are attracting significant interests for improving process efficiency and material quality. It has been previously shown that the simultaneous application of ultrasonic vibrations (frequency of 20 kHz and vibration displacement of 23 μm) during continuous wave (CW) CO_2 laser surface melting results in melt expulsion and formation of surface holes. In this paper, a systematic evolution of geometric features (hole depth, diameter, aspect ratio, and taper) and quality parameters (material build-up, spatter, recast layer thickness, and heat affected zone) of holes with laser irradiation time (0.05, 0.1, 0.2, 0.25, 0.35, 0.75, and 1.25 s) for the ultrasonic vibration-assisted CW CO_2 laser surface drilling of AISI 316 stainless steel is investigated. Also, a multi-step finite element analysis, taking into account the observations of melt expulsion from high speed photography, is presented for the prediction of laser drilled hole volume. The results indicate that the laser melting regime of the continuous wave laser-material interactions can be extended for drilling of materials, expanding the applications of these widely used lasers for flexible manufacturing.

1. Introduction

Pulsed laser drilling, in the laser-material interaction regime of surface melting, is commonly used for machining of 0.5–3 mm holes in a range of applications, as described in Dahotre and Harimkar (2008). The drilling of sub–1 mm cooling holes in the aerospace components is one of the most of important applications of the pulsed laser drilling and is discussed by French et al. (2003). The laser drilling process involves irradiation of high intensity pulses that cause surface melting and evaporation at the surface of the melt film. Zhang and Faghri (1999) described that while some material removal occurs by surface evaporation, the dominant mechanism of material removal remains the melt expulsion during laser drilling. Wagner (1974) reported that the melt expulsion is a direct result of evaporation induced recoil pressure on the surface of the melt. When the pressure on the surface of the melt film exceeds the surface tension forces, the melt is pushed radially out, creating a hole by melt expulsion. Assist gases are often used to facilitate the melt expulsion during laser drilling. As Low et al. (2002) discussed, the efficiency of material removal (drilling rate) and the quality of drilled holes depend on the dynamics of the melt flow during laser drilling. Significant efforts have been made to improve the material removal rates and quality of holes during laser drilling. Chen et al. (1996) studied the effect of the peak power and the pulse format on the quality of the laser drilled holes. Low et al. (2000) investigated the effect of assist gas (O_2, Ar, N_2, and Air) on the thickness and geometry of the surface spatter formed during laser drilling and reported a significant reduction in spatter thickness in the case of O_2 assist gas. It has also been demonstrated by Low et al. (2001) that the material ejection processes during laser drilling can be effectively controlled by temporal pulse train modulation for improving the material removal rate and quality of laser drilled holes. Lau et al. (1994) and Yue et al. (1996) also reported that the simultaneous application of ultrasonic vibrations during pulsed laser drilling improve the material removal and quality of laser drilled holes. With this approach of ultrasonic vibrations-aided pulsed laser drilling, about 20% increase in hole depth and about 30% reduction in heat affected zone were reported by Lau et al. (1994) for aluminum matrix composites. However, even with these advances, laser drilling of large aspect-ratio holes with acceptable surface quality and reproducibility is still a challenge in adopting the technology for wider applications.

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http://dx.doi.org/10.1016/j.jmatprotec.2016.01.025

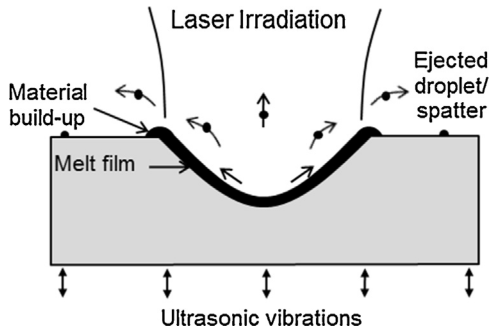

Fig. 1. Schematic of the melt expulsion in the form of upward melt flow and droplet ejection leading to hole formation during ultrasonic vibration-assisted laser surface drilling.

Continuous wave (CW) laser surface melting, with steady state melting conditions reached at sufficiently high laser scanning velocities, results in the formation of well-defined resolidified bead on the surface. A continuous laser irradiation at a spot (i.e. stationary irradiation without scanning) on the surface also forms a well-defined melt pool, albeit with some surface rippling in some cases. These characteristics are very useful for surface modification of materials, and hence, continuous wave lasers are most appropriate for laser surface engineering applications as described in Ion (2005). The continuous wave lasers are also used in cutting applications where the assist gases expel the melt from the bottom of the cutting front/kerf. However, the use of continuous wave lasers, even with the presence of assist gases, in material drilling applications is limited. Recently, it has been observed by Alavi and Harimkar (2015a) that the simultaneous application of ultrasonic vibrations (20 kHz) during continuous wave CO_2 laser surface melting of stainless steel destabilizes the melt film and facilitates the melt expulsion. The melt expulsion resulted in the formation of well-defined craters with resolidified surface films. The laser surface melting experiments under the influence of ultrasonic vibrations were conducted for the laser power of 900 W, laser irradiation times in the range of 0.35–0.45 s, and the working distance (i.e. the distance between the laser head and the surface of the sample) of about 50 mm. It has also been shown that the melt expulsion, in the form of sideways melt flow and droplet ejection, initiates when the critical melt film thickness is reached. The observation of melt expulsion during laser surface melting under the influence of ultrasonic vibrations presents a unique possibility of laser drilling with a continuous wave laser. The schematic showing the melt expulsion and hole formation during the ultrasonic vibrations-assisted continuous wave laser surface drilling is shown in Fig. 1.

The preliminary laser drilling experiments, reported by Alavi and Harimkar (2015b), have shown that the high aspect ratio holes can be drilled by reducing the working distance to about 15 mm for the similar laser processing and ultrasonic vibration parameters. It has also been observed that the ultrasonic vibration parameter, especially the vibration displacement, for the given ultrasonic frequency (20 kHz) influences the geometric parameters of the laser drilled holes. In contrast to earlier investigations by Lau et al. (1994) and Yue et al. (1996) where ultrasonic vibrations were simultaneous applied during pulsed laser drilling (a well-established laser drilling process in itself), the proposed ultrasonic vibration-assisted continuous wave laser drilling extends the energy-efficient laser melting (no drilling) regime for laser drilling applications and enables continuous (instead of discontinuous pulsed) drilling of materials. Since continuous and pulsed wave laser outputs result in different laser-material interactions (primarily surface melting for continuous wave lasers; melting with extensive surface evaporation, generation of recoil pressure, and use of assist gas for pulsed lasers), direct comparison between continuous wave and pulsed laser machining/drilling is difficult. However, performing laser drilling in CW mode offers benefits related to energy/process efficiency and quality of machined surfaces. The pulsed laser drilling is performed with a very high peak power (up to 20 kW) but low pulse repetition rates with long pulse off times as described in Roos (1980) The material surface cools very fast during this pulse off time, i.e. the surface needs to reheated/remelted again during each subsequent pulse to create melt expulsion as reported by Dahotre and Harimkar (2008). In continuous wave laser drilling under the influence of ultrasonic vibrations, the material removal is primarily in melting regime and sufficiently low power (950 W in this case) continuous output is enough to facilitate melt expulsion. Furthermore, there are no off times in continuous wave laser drilling, so the melting is continuous (i.e. no intermittent cooling as in case of pulsed laser drilling) and performed in much shorter time. With efficient material removal under the influence of ultrasonic vibrations, the proposed continuous wave laser drilling is likely to offer benefits related to material removal rate and machined surface quality compared to conventional pulsed laser drilling. With the widespread use of continuous wave CO_2 lasers in industry, the proposed laser drilling approach is likely to expand the applications of these lasers for flexible manufacturing.

While the preliminary studies have established the possibility of laser drilling with the proposed ultrasonic vibrations assisted-laser surface melting, it becomes important to establish the mechanisms of laser drilling under the influence of ultrasonic vibrations and investigate the evolution of geometric and quality aspects of the laser drilled holes with the laser irradiation time. In this paper, high speed photography is used to trace the sequence of processes, leading to formation of hole with the laser surface melting under the influence of ultrasonic vibrations (laser power of 950 W, working distance of 15 mm, ultrasonic vibration frequency of 20 kHz, and vibration displacement of 23 μm). Also, the results of detailed and systematic investigations on the evolution of geometric parameters (hole diameter, depth, aspect ratio, taper angle, and material removal rate) and quality parameters (build-up material at the hole rim, recast layer thickness on the hole walls, microstructure in recast layer, and heat affected zones) with the laser irradiation time in the range of 0.05–1.25 s (for the given specific laser processing and ultrasonic vibration parameters) are presented. A two-dimensional finite element model (heat transfer) based on critical time of melt expulsion observed from high speed photography is proposed for the prediction of material removal volume during laser drilling under the influence of ultrasonic vibrations. The predictions of the laser drilled hole volumes from the heat transfer model were compared with the experimental results for the investigated laser irradiation times.

2. Experimental procedure

The ultrasonic vibration-assisted laser surface drilling setup consisted of a continuous wave (CW) CO_2 laser (Ferranti, Manchester, UK), a ultrasonic power supply, and a 13-mm diameter threaded titanium alloy probe/horn (Sonics & Materials, Inc., Newtown, CT). The experiments were performed on 3.5 mm thick AISI 316 stainless steel specimens (17.45% Cr, 11.81% Ni, 2.5% Mo, 0.05% C, 1.35% Mn, 0.68% Si, 0.011% S, 0.047% P, and balance Fe by weight). Each steel specimen, surface finished by polishing using 400 grit SiC papers followed by sand blasting, was screwed on the threaded ultrasonic probe. The schematic of the experimental setup is shown in Fig. 2. The laser surface melting was performed with a laser power of 950 W and working distance of 15 mm for a range of laser irradiation times: 0.05, 0.10, 0.20, 0.25, 0.35, 0.75, and 1.25 s.