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Melt expulsion during ultrasonic vibration-assisted laser surface processing of austenitic stainless steel

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ABSTRACT

Simultaneous application of ultrasonic vibrations during conventional materials processing (casting, welding) and material removal processes (machining) has recently been gaining widespread attention due to improvement in metallurgical quality and efficient material removal, respectively. In this paper, ultrasonic vibration-assisted laser surface melting of austenitic stainless steel (AISI 316) is reported. While the application of ultrasonic vibrations during laser processing delays the laser interaction with material due to enhancement of surface convection, it resulted in expulsion of melt from the irradiated region (forming craters) and transition from columnar to equiaxed dendritic grain structure in the resolidified melt films. Systematic investigations on the effect of ultrasonic vibrations (with vibrations frequency of 20 kHz and power output in the range of 20–40%) on the development of microstructure during laser surface melting (with laser power of 900 W and irradiation time in the range of 0.30–0.45 s) are reported. The results indicate that the proposed ultrasonic vibration-assisted laser processing can be designed for efficient material removal (laser machining) and improved equiaxed microstructure (laser surface modifications) during materials processing.

1. Introduction

Laser processing offers interesting possibilities to modify the microstructure, phases, composition, residual stresses, and topography of the surfaces of materials through a range of laser–material interactions such as heating, melting, surface vaporization, ablation, and shock peening [1–6]. Among these laser–material interactions, surface melting is by far the most important regime for the practical applications of lasers in materials processing. The laser surface melting has been extensively used for microstructural refinement, surface alloying, and composite surfacing [7–10]. The laser surface melting is also very important in laser material removal (machining) and joining processes [11,12]. For example, melt expulsion from the drilling or cutting surfaces is a dominant mechanism of material removal at lower power laser machining while surface evaporation becomes dominant at higher laser powers [13]. Coaxial assist gas jets (inert gases in fusion cutting and oxygen in reactive fusion cutting) are generally used to expel thin melt films from the drilling and cutting kerfs. The melt expulsion occurs when momentum transferred to the thin melt films exceeds the surface tension forces. The rate/speed of machining and quality of the machined surfaces during laser drilling and cutting are influenced by the rate of melt expulsion and dynamics of melt flow [14]. For example, recast layer on the hole walls, spatter around the periphery of the laser drilled holes, and low hole aspect ratios are primarily due to incomplete or inefficient expulsion of the melt during laser drilling [15,16]. While significant efforts have been made to optimize the design of the assist gas nozzles, gas pressures, and gas compositions, it is challenging to improve the machining speed and quality of laser machined surfaces especially in the surface melting regime of laser drilling/machining.

Significant efforts have been made in the past to use the desirable effects associated with the application of ultrasonic vibrations during conventional manufacturing, resulting in the emergence of a new field of ultrasonic vibration-assisted manufacturing [17,18]. The ultrasonic vibration-assisted machining is widely investigated for precision manufacturing of brittle ceramics. In this case, the repeated impacts of the vibrating tool facilitate material removal by micro-chipping. It has also been observed that the application of ultrasonic vibrations (frequency: 40 kHz; amplitude: 3 μm) enables the machining in ductile regime for the brittle ceramics, especially at low depth of cut [18]. The process has been investigated for both traditional and non-traditional machining of materials with and without use of abrasive slurry (mechanical drilling, diamond cutting, lapping, electro-discharge machining, etc.) [19,20]. It has been reported that the application of ultrasonic vibrations (frequency: 61.5 kHz) in the micro electro-discharge machining increases the aspect ratio of the microholes by 132%

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in stainless steel [21]. A few attempts have also been made to use the desirable effects of ultrasonic vibrations during laser machining (drilling) of materials. For example, Zheng and Huang reported application of ultrasonic vibrations (frequency: 40 kHz; amplitude: 2.5 μm) during femtosecond pulsed laser (Ti-Sapphire laser) micro-drilling of the Nitinol samples with an improvement in hole wall surface quality and higher hole aspect ratio [22]. Chiu et al. also investigated the ultrasonic vibration (frequency: 20 kHz; amplitude: 10 μm) assisted pulsed excimer laser (KrF laser) machining and cleaning of the PZT materials [23]. In these studies on ultrasonic vibration assisted laser machining [22,23], pulsed lasers were used and the dominant material removal mechanism was ablation. The pulsed lasers such as pulsed KrF and Ti:Sapphire lasers are traditionally used for drilling, and the application of ultrasonic vibrations in these studies was to facilitate the removal of ablated debris and particles from the surface to improve surface quality and machining rate.

While most of the reported traditional and non-traditional machining processes utilize the desirable effects of the application of ultrasonic vibrations in the solid state (micro-chipping, brittle-ductile transition, and removal of ablated debris), the application of ultrasonic vibrations also offers unique effects in manufacturing that involves melting of materials. The ultrasonic vibrations have been utilized for improving the metallurgical quality and refining the grain structure of the metal/alloy castings. For example, Jian et al. reported that the application of ultrasonic vibrations (frequency: 20 kHz; amplitude: 56.7 μm) during casting of an aluminum alloy (A356) resulted in the reduction of grain size of the eutectic silicon from 26 to 2 μm [24]. It is well established that mechanical and electromagnetic stirring of the melt during casting facilitate the columnar to equiaxed transition (CET) of the grain structure, resulting in grain refinement [25].

The ideas have been extended for improving the microstructure of weld metal during ultrasonic vibration assisted arc welding process. For example, Cui et al. reported the elimination of the unmixed zone in the welding of the super-austenitic stainless steel in the presence of the ultrasonic vibrations (frequency: 20 kHz) [26]. Cui et al. also observed significant reduction in columnar dendritic microstructure with the application of ultrasonic vibrations during shielded metal arc welding (SMAW) of AISI 304 stainless steel. It was reported that the amount of columnar dendritic microstructure decreased from about 95% to 10% with increasing ultrasonic power output from 0% to 90% [27]. Most of the processes that utilize the desired effects of ultrasonic vibrations during solidifying melt exhibit relatively slow cooling and solidification rates. The application of ultrasonic vibrations to rapidly solidifying melt is not well investigated. As rapid melting/solidification is encountered during several laser manufacturing processes such as surface modification (laser melting, alloying, cladding, and composite surfacing), forming (laser welding/joining), and material removal (laser machining) processes, the application of ultrasonic vibrations during laser processing presents a great potential for improving the microstructure, metallurgical quality, and material removal rates of the processed materials. In this paper, a new ultrasonic vibration-assisted laser surface processing approach is presented for surface melting of AISI 316 stainless steel. The laser processing was conducted with simultaneous application of ultrasonic vibrations (20 kHz) in the surface melting regime, and the effect of ultrasonic vibrations on the development of microstructure in the resolidified melt pool is analyzed.

2. Experimental procedure

A schematic of the set-up for ultrasonic vibration-assisted laser surface processing is shown in Fig. 1(a). The set-up consisted of a threaded titanium alloy probe (horn) of 13 mm diameter and 139 mm length. The ultrasonic power supply delivered the power output of 750 W at a fixed frequency of 20 kHz (Sonics & Materials, Inc, Newtown, CT). AISI 316 austenitic stainless steel (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) tips of 2 mm thickness were used as specimens for ultrasonic vibration-assisted laser surface processing. The surfaces of the steel specimens were polished with SiC paper (1200 grit) followed by cloth polishing with alumina powder (0.5 μm particle sizes) to render mirror finish. To increase the absorption of laser radiation, the specimen surfaces were etched for 20 s using a common etchant for 300 series stainless steels (Carpenters stainless steel etch; 6 mL HNO_3, 122 mL HCl, 122 mL Ethanol, 8.5 g $FeCl_3$, and 2.4 g $CuCl_2$). The specimens were immediately washed and dried after etching. Each specimen tip was then screwed on the threaded end of the ultrasonic probe. For the ultrasonic-vibration assisted laser surface processing, a continuous wave CO_2 laser with laser power of 900 W was irradiated on the vibrating specimens. The laser beam diameter was about 100 μm at the exit of the laser head. The laser processing was conducted with the defocused beam (about 7 mm in diameter) with the distance from the laser head to the surface of the specimen of about 5 cm. The laser beam energy profile was Gaussian, and the beam was irradiated perpendicular to the vibrating surface (i.e. vibration amplitude parallel to the beam as shown in Fig. 1(a)). The laser processing was conducted for three irradiation times: 0.30, 0.35, and 0.45 s. For each laser irradiation time, the processing was conducted with three ultrasonic vibration power outputs: 20%, 30%, and 40%. The power output controls the amplitude of vibration at the surface of the specimen tip. A 3D optical profilometer (Nanovea, Irvine, CA) was used to measure the vibration displacement at each power output. The optical profiler detects a step corresponding to vibration displacement in the surface profile when the ultrasonic system is turned on during the measurement. The surface profiles for the ultrasonic vibrations at the specified power outputs are shown in Fig. 1(b). The vibration displacements of 23, 37, and 51 μm were measured for the power outputs of 20%, 30%, and 40%, respectively. The laser irradiation times and ultrasonic power outputs used in this investigation were the optimum parameters that resulted in the laser–material interaction (heating/melting), and showed transition in the melt flow behavior for the case of surface melting. The laser processing and ultrasonic vibration parameters for the three sets of experiments are summarized in Table 1. The phase identification of the laser processed specimens was performed using an X-ray diffractometer (BRUKER AXS, Inc, Madison, WI) operating with Cu Kα radiation. The diffraction angle (2θ) was varied between 20 and 100°. The surface profiles of the laser processed specimens were also recorded using 3D optical profilometer (Nanovea, Irvine, CA). A scanning electron microscope (JEOL Ltd, Tokyo, Japan) was used to characterize the microstructures at the surface and in the polished cross sections of the laser processed specimens. ImageJ software was used for the measurement of melt film thickness, and at least 9 measurements were taken for each sample on the crater walls from the cross-sectional SEM micrographs.

3. Results and discussion

3.1. Laser surface processing for irradiation time of 0.30 s

The surface and cross sectional SEM micrographs of the steel samples laser irradiated for 0.30 s with and without the simultaneous application of ultrasonic vibrations are presented in Fig. 2. The sample laser irradiated without application of ultrasonic vibrations exhibited a well-defined central melted region with sur-