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Fiber laser induced surface modification/manipulation of an ultrasonically consolidated metal matrix

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ABSTRACT

Ultrasonic Consolidation (UC) is a manufacturing technique based on the ultrasonic joining of a sequence of metal foils. It has been shown to be a suitable method for fiber embedment into metal matrices. However, integration of high volume fractions of fibers requires a method for accurate positioning and secure placement to maintain fiber layouts within the matrices. This paper investigates the use of a fiber laser for microchannel creation in UC samples to allow such fiber layout patterns. A secondary goal, to possibly reduce plastic flow requirements in future embedding processes, is addressed by manipulating the melt generated by the laser to form a shoulder on either side of the channel. The authors studied the influence of laser power, traverse speed and assist gas pressure on the channel formation in aluminium alloy UC samples. It was found that multiple laser passes allowed accurate melt distribution and channel geometry in the micrometre range. An assist gas aided the manipulation of the melted material.

1. Introduction

The primary mechanism behind channel production with a laser is that the heat of the laser is used to generate channels by melting or vapourisation of the material. Especially in the case of melting the material, an assist gas is needed to expel the molten material out of the groove. As opposed to laser cutting, channel production via laser-use can be more considered as a 3D process taking into account the height, width and depth of the channel.

Within the range of laser machining processes the production of channels with the aid of an assist gas has been established as laser grooving (Chryssolouris et al., 1988). Chryssolouris et al. (1988) found that a linear relationship between the groove width and power density exists. A theoretical model for the depth prediction was introduced by Choi and Chryssolouris (1995) in which it was predicted that an increase of the combined effect of power and traverse speed results in larger depths. Lallemand et al. (2000) studied the influence of different gas inlet angles on groove depth and width. He concluded that both depth and width are dependent on the material itself (heat conduction properties) as well as on different gas inlet angles. The same results have been found by Li et al. (2005) who studied the melt removal rate for three different materials and found that the highest heat conductor produces shallow and wide channels. Mai and Lin (2003) studied the influence of a centred gas pressure in combination with an off-axis jet at various angles on the depth. They found that at different angles, in combination with different gas pressures, the melt removal rate varied; as well as the appearance of dross on the sides of the groove. O'Neill et al. (2001) showed that the groove depth is dependent on power and independent of assist gas; the assist gas is only required to remove the material out of the groove. Recent research has been carried out by Stournaras et al. (2009). Their theoretical model for a pulsed laser predicted that the groove depth is dependent on the traverse speed as well as the laser power.

A large proportion of the research conducted on laser grooving so far has been focused on theoretical predictions with relatively few examples of practical research. Few researchers (Mai and Lin, 2006) have addressed the relationship between melt removal and melt displacement for laser grooving which is of particular interest for 3D micromachining processes that demand precision and accuracy for manufactured parts (Meijer et al., 2002). Spatter formation is a common problem in laser micromachining and originates from ejected material that is not completely removed from the channel, drilled hole (Low et al., 2003) or cut kerf (Riviero et al., 2008). A solution to prevent spatter formation in micromachining is the use of pulsed lasers which allow high peak power densities that lead to vapourisation of the material (Bandyopadhyay et al., 2002). Jha et al. (2007) generated microchannels in aluminium in the micrometre range and found that reacting forces with the material due to energy densities might lead to the deformation of the channels. Kumar and

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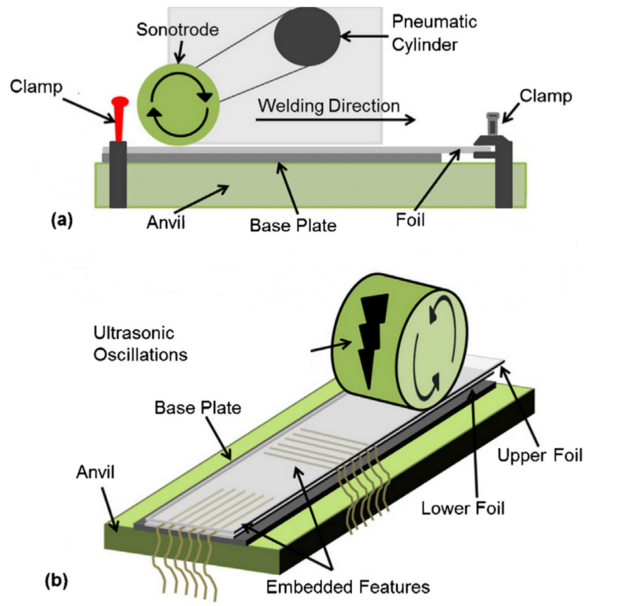

Fig. 1. Schematic overview of the Ultrasonic Consolidation process (a) front view and (b) embedding features.

Gupta (2010) stated that higher fluencies lead to the ejection of melt and vapourisation in laser drilling. For cleaner edges i.e. less spatter, lower fluencies had to be used.

This paper investigates the use of a fiber laser for the production of microchannels in ultrasonically consolidated samples. Ultrasonic Consolidation (UC) is an additive manufacturing method based on the ultrasonic welding of a sequence of metal foils. The process is suited to producing complex 3D metal parts by combining ultrasonic metal welding and Computer Numerical Control (CNC) milling techniques (White, 2003). A schematic overview of the process is given in Fig. 1(a).

Two key aspects of UC are: Firstly, bond formation is achieved at temperatures lower (typically ≤50%), than the melting temperature of the foil material (Kong, 2004). Secondly, highly localised plastic flow occurs during ultrasonic excitation of the metal foil (Langenecker, 1966). These two aspects (solid state low temperature processing and high plastic flow) allow certain components, prone to damage or sensitive to high temperatures, to be embedded via UC (Cheng et al., 2007) as schematically displayed in Fig. 1(b). In particular, the integration of different types of active and passive fibers seems to be a promising application for UC to produce adaptive composites (Kong and Soar, 2005). In order to truly exploit the potential of UC as an application for adaptive composite manufacturing high volume fractions of fibers must be realised for effective active structure control and monitoring. Latterly, Friel and Harris (2010) embedded a total of ten NiTi Shape Memory Alloy fibers within an Al 3003 (O) foil matrix and discussed that fibers have a weakening effect on foil to foil bond formation during UC. In addition, UC sonotrode oscillation amplitudes are necessary to induce sufficient material flow in the matrix and void closure (Yang et al., 2009) around a higher number of fibers. By increasing the UC sonotrode oscillation amplitude the fibers to be embedded can be adversely affected. To reduce the required amplitude, and thus the necessary matrix plastic flow, Kong and Soar (2005) used a hard fiber to form a groove in the matrix material prior to fiber placement and subsequent UC.

In this paper the authors present an approach to produce channels in UC samples with the use of a fiber laser. A schematic overview of the process can be seen in Fig. 2. UC samples would be irradiated by the fiber laser to create a channel (Fig. 2(a)). By manipulating the resulting spatter/melt formation in combination with the assist gas the spatter/melt on either side of the channel boundaries could be distributed (Fig. 2(b) and (c)), which would in turn reduce the required level of plastic flow during future fiber embedding (Fig. 2(d)).

The main aim of the channel/shoulder generation for future fiber integration was as follows: accurate channel geometries would likely enhance accurate high volume fiber placement and reduce fiber distortion, while applying oscillations and pressure during UC. Additionally, it was proposed that the shoulders would provide additional material which would facilitate plastic flow around embedded fibers during UC.

2. Methodology

All of the laser experiments were conducted on samples consisting of aluminium alloy 3003-H18. The material was chosen due to its use in earlier UC studies on fiber embedding (Yang et al., 2010) which allows comparison of the effects of laser processing. The alloy was supplied as a foil by United Aluminum, USA (24 mm wide and 100 μm thick) and had a nominal composition of: Al 97 wt%, Mn 1.5 wt%, Si 0.6 wt%, Fe 0.7 wt%, Cu 0.2 wt%.

2.1. UC sample manufacture

Prior to the laser processing, samples were manufactured using Loughborough University's Alpha 2 UC machine. The machine was supplied by Solidica Inc., USA, and had been used in several previous UC studies (Kong, 2004; Friel et al., 2010). Variable process parameters of the UC machine are: sonotrode oscillation amplitude (μm), welding speed (mm/s) and welding force (N). These parameters were maintained at constant values of 40 mm/s for welding speed, 1400 N for welding force and 20 μm for the sonotrode oscillation amplitude. The manufacturing procedure for the samples was consistent with previously published work (Masurtschak and Harris, 2011).

2.2. Laser processing

The laser used in this study was a Trumpf TruFiber 300 W laser with a wavelength of 1.085 μm. A fiber laser was selected at this stage of investigation due to beam quality factors of $M^2 \leq 1.2$ which allowed focusing to a small spot size, hence a high power density and a Gaussian distribution of the beam (Han and Liou, 2004). It was predicted that higher beam qualities exhibiting different intensity distribution profiles would lower the possibility to manufacture semi-circular shaped channels, which would likely enhance secure positioning of circular fibers. Additionally, it was proposed that higher order modes would modify the heat input into the material, which could possibly make the flow pattern of the melted material more difficult to control (Han and Liou, 2004).

All experiments on the Trumpf TruFiber 300 W were carried out in continuous wave mode with a calculated spot size of 13.8 μm. The irradiance of the incident beam corresponded to 1.48×10^8 W/cm^2 for 200 W and 2.23×10^8 W/cm^2 for 300 W. The assist gas was supplied through a conical cutting nozzle. The gas utilised throughout the experiments was air. A schematic representation of the set-up can be seen in Fig. 3.

The UC sample was fixed on a CNC working table which could be operated in the *X* and *Y* direction. Experiments were carried out by varying the traverse speed (mm/s), laser power (W) and assist gas pressure (MPa). The scanned laser channels had a length of 15 mm. Table 1 lists the parameters variations that were used.

The beam was focused above the surface of the aluminium material which is consistent with laser cutting operations (Wandera