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Enabling Dissimilar Fibre Embedding and Explicit Fibre Layout in Ultrasonic Consolidation

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ABSTRACT

Ultrasonic Consolidation (UC) is a manufacturing technique based on the ultrasonic metal welding of a sequence of metal foils which are bonded to one another in a layer by layer manner. It combines the ability of additive and subtractive manufacturing techniques to create complex three-dimensional shapes. Due to moderate applied pressures and the relatively low temperatures experienced by a sample during manufacture, UC operates as a solid-state process. UC could potentially enable the fabrication of smart structures via integration of sensor, actuator and reinforcement fibres within a single metal matrix.

Previous issues with the optimal placement of fibres directly between foils during UC have been identified. Also, different types of integrated fibres require different UC process conditions and thus present complications when integrating them in combination. To truly exploit the full potential of UC for smart structure capabilities it is envisioned that a high volume fraction of dissimilar fibres are required to be integrated together within a single metal matrix structure.

Research on a new method to consolidate fibres securely and more accurately during UC is presented. Channels created prior to UC within metal matrix composites are investigated as a method to aid the embedding of high volume fractions of different fibres in unison without damage. Initial research using a 200 W fibre laser as an enabling tool to create channels of specific geometry onto a previously UC processed surface is detailed. The research verifies that controlled channelling on a UC surface is possible and that channel geometry is dependent on: laser traverse speed, laser beam power, and shroud gas flow rate.

1. INTRODUCTION

Ultrasonic Consolidation (UC) is a hybrid additive/subtractive manufacturing method based on the ultrasonic metal welding of a sequence of metal foils with intervallc material removal through the employ of three axis computer numerical control (CNC) contour milling. The process was invented, patented and is provided by Solidica Inc., USA [1]. A power supply converts the mains electricity alternating current frequency to an ultrasonic value (typically 20 kHz), which is then converted in a lead zirconate titanate based actuating transducer to mechanical energy. This then mechanically drives a half wave booster and a sonotrode; with the latter applying the ultrasonic oscillations to a metal foil material under a compressive normal force (see Figures 1 and 2). The bonded foil solid metal object, or metal ‘patch’ deposition on an existing object, is then contour milled using an integrated CNC machine to create the desired layer geometry at which point the process is continually repeated to obtain the final three-dimensional component in a layer by layer fashion (see Figure 3).

The sonotrode induced foil material oscillations and the relatively thin structure (typically 100 to 150 µm) of the foil allow energy to be passed through and imparted at the foil/component interface. The localised energy, oscillations and pressure allow metal plastic flow with associated localised deformation and bonding at a lower temperature than the bulk melting temperature of the foil material (aluminium alloys <150 °C, compared to their melting temp of ~600 °C), resulting in solid state
bonding at the component/foil interface at relatively low pressures (<300 kPa) [2]. This process results in true metallurgical bonds being formed between the deposited metal foil layers. UC is classified as a rapid solid state deposition process and has the following advantages over many other manufacturing processes:

- UC allows the embedding of temperature and pressure sensitive objects into solid metal matrices [3, 4, 5]. (E.g. SiC fibres, Shape Memory Alloy (SMA) fibres, optical fibres, fibre Bragg gratings, electronic sensors, etc). This is permitted due to the low temperature high plastic flow of the metal matrix that is encountered during UC.
- There is no atmospheric control with UC due to the solid state room temperature nature of the material processing.
- UC has no safety hazards associated with the formation of liquid metal, metal fumes, powder handling, dust or other molten metal handling issues.
- Due to the absence of a liquid to solid transformation UC minimises residual part stresses and net shape distortion in comparison to thermal based processes.
- UC deposition rates are higher than for many layer manufacturing processes due to a far larger “deposition spot size” (25.4 mm wide foil layers are used) and lack of any lengthy post processing procedures.
- UC can be used to bond materials that are metallurgically incompatible in fusion processes [6]. (E.g. Al, Ti, Cu, Ni, Stainless Steel, etc).
- UC is energy efficient, consuming as little as 5% of the energy required for more conventional welding processes [7].

Langenecker [8] noted a phenomenon termed “acoustic softening” during the ultrasonic processing of metals. This phenomenon results in the low temperature, (generally ≤50% of the metals’ melting temperature); plastic flow/deformation of a metal material when ultrasonic excitation energetically interacts, reorients and expands dislocations within a polycrystalline metal.

During UC this phenomenon has been exploited by users to embed a variety of elements within aluminium matrices, (see Figure 4) such as: shape memory alloy fibres [2], single mode optical fibres [9], and SiC fibres [5], and various other components (see Figure 5). However an increasing volume fraction of embedded fibres has been identified as a hindrance of the ultrasonic bonding process [3]. This is owing to the mechanism of object embedding being facilitated by matrix plastic flow but at the same time the higher volume of fibres requiring a greater level of plastic flow than is available during the UC process. Greater matrix plastic flow can be obtained during UC by increasing the sonotrode oscillation amplitude and/or the normal force although this then exposes delicate fibres to forces during UC that often result in fibre failure.

In addition to a limit on maximum plastic flow available and embedded fibre damage there is an issue of controlled explicit fibre layout patterns being achieved and maintained during the rolling and perpendicular oscillations experienced by the embedded fibres during UC. The movement of the fibres in a finished UC part can be illustrated using micro computed tomography (µCT) imagery (Figure 6).

For the present work the authors have proposed a method to improve fibre volume fractions and explicit fibre layout during UC.

2. FOCUS OF THE PRESENT STUDY

To help eliminate the difficulties of: increased UC amplitudes, lower embedded fibre volume fractions, and indefinite and insecure fibre placement during embedding the researchers had devised a potential solution. This potential solution was based around a system of designed channel apertures with novel features for the UC of multiple differing embedded fibres (Figure 7). These channels were sequentially engineered into the surface of the matrix material prior to UC processing. A raised ‘shoulder’ at the outer edge of the engineered channel was expected to permit the use of lower UC amplitudes whilst obtaining sufficient matrix material plastic deformation by reducing the size of the initial void surrounding the fibre. Through the use of these channels higher volume fractions at lower
UC amplitudes and pressures whilst maintaining UC foil/foil bond quality were postulated to be achievable. The channels were also expected to aid in the positioning of fibres both pre and post UC processing.

The envisioned method of channel production is depicted in Figure 8 and involves the application of an infrared (IR) laser. Generating the channels depicted in Figure 8(c) (50–75 µm depth and ~100 µm diameter) would initially require a melt pool to be produced at the matrix surface via a photo-thermal reaction resulting from IR laser irradiation, as illustrated in Figure 8(a). Photo-thermal inducement of melting could be controlled by the laser/material interaction [10]. Secondly, the shoulder features would be formed by the manipulation of the melt pool by a coaxial inert gas jet to expunge the molten matrix material out of the formed channel and onto the matrix material surface (Figure 8(b)). This process was akin to that of laser drilling metals with pulsed IR lasers [11] where the material removed was ejected and deposited inadvertently on the surface surrounding the hole as unwanted spatter.

3. METHODOLOGY

The channel enabling tool used for the initial research was a 200 W infrared fibre laser (SPI Lasers Plc.) with a stable Gaussian beam profile. Fibre lasers offer a wide range of advantages such as high beam qualities, high power densities which favour small spot sizes and outstanding thermal properties [12-16]. To evaluate the capability of a laser generating channels with a diameter of approximately 100 µm and a depth of 50–75 µm a fibre laser set-up shown in Figure 9 was employed.

Though there were many laser processing variable parameters which were also dependant on the specific material energy absorption [17], three main parameters were considered to be the most influential ones on the ablation process: laser power (W), shroud gas flow rate (l/min) and laser traverse speed (mm/min) [18-20]. To show the interrelationships between these three parameters, a test range combining the parameters was established. The processing gas utilised was compressed air due to availability and proven results [21].

The marking scheme for the laser was set as a group of parallel lines across the surface of the post-UC processed foil surface. The laser traverse speeds used were: 50, 100, 150, 200, 250 and 300 mm/min. The laser powers used were: 60, 80, 100, and 120 W. The gas flow rates used were: 10, 15, 20, and 25 l/min. These parameters were used in combination and the resultant channels were measured using optical microscopy as well as white light interferometry to obtain topographical data.

The aluminium foil used for the UC-processing and subsequent laser scanning was Al 3003 H18 at a foil thickness of 100 µm and width of 25.4 mm.

4. RESULTS AND DISCUSSION

4.1 Results of Laser Channelling

Visual inspection via microscope of the channels showed that two areas represent the channel. The first was the outer channel with the shoulder feature and the second was the inner channel in which the fibres were to be placed (see Figure 10). Two different diameters for the channels were measured and examined as a result of this identification; one measurement for the inner and outer diameter respectively, however the total affected width was used as the main measurement, (i.e. the channel with included shoulder features).

Figure 11 presents the effects of laser power; gas flow rate and laser traverse speed on the channel and shoulder region width. Variation of laser power was identified as one of the most significant parameters on the channel geometry. The channel width for all measurements was always greater than or equal to 50 µm and this diameter occurred at relatively low laser powers. As the typical embedded fibre diameter used for UC is 100 µm this minimum size was smaller than required. The higher the laser power input and therefore the power density, the larger the channel width was. Chryssolouris [22] discovered a linear relationship between the laser power and the cut width during a laser cutting
process. The relationship states that with a constant laser beam diameter, an increase in laser power causes an increase in cut width, due to the resulting increase in power density.

The laser traverse speed had a significant influence on the channel width. At the slowest laser traverse speed of 50 mm/min, the widest channel width achieved was 250 µm, at a laser power of 120 W and a gas flow rate of 15 l/min. The channel width decreased with greater laser traverse speeds and was the lowest, under 200 µm, at a speed of 300 mm/min. This observation is attributed to the fact that the faster the laser traverse speed the shorter the laser/material interaction time in which heat could significantly increase within the material and thus resulted in a narrower channel width.

The influence of the gas flow was less than the influence of laser traverse speed and laser power. At a laser traverse speed of 50 mm/min and 100 mm/min respectively, the width of the channel created using different gas flow rates differed from 175 µm to 250 µm and 125 µm to 200 µm at a laser power of 120 W. The first three graphs in Figure 11 show that a gas flow of 25 mm/min resulted in smaller channel widths. The reason for this was hypothesised to be that at higher gas flow rates the molten Al material cools down more rapidly due to greater forced convection and therefore less material could be expelled from the laser/material interaction zone. At greater laser traverse speeds the influence of the gas flow rate became less prominent and resulted in similar channel widths for the various different gas flow rates. At slower laser traverse speeds the area of the molten material was assumed to increase due to more laser penetration time, however a greater gas flow rate could not expel the larger volume of molten material out of the channel. Therefore the molten material remained within the channel resulting in a smaller channel width [23]. Future work was intended to be conducted to ascertain whether a proportional relationship exists between the gas flow rate and the laser traverse speed.

In Figure 12 the inner channel size for various laser traverse speeds, laser powers and gas flow rates are graphically depicted. In contrast to Figure 11, inner channels were only generated at higher laser traverse speeds greater than or equal to 150 mm/min. The largest achieved inner channel size (68 µm) was exhibited at a laser traverse speed of both 200 mm/min and 250 mm/min. Laser traverse speeds of 150 mm/min and 300 mm/min exhibited smaller channel widths. This occurrence was hypothesised to be due to the higher laser traverse speeds causing less laser material interaction time and lower laser traverse speeds resulting in too large a heat level causing the expelled material to flow back into the created channel. Additionally, Figure 12 highlights that gas flow rate does have an impact on inner channel creation. A gas flow rate of 10 l/min seemed insufficient to achieve surface penetration at all. Only higher gas flow rates seemed to be able to expel the molten material from within the channel.

The influence of laser power, allowing for higher power densities to be achieved, was significant in creating inner channels. No channels were created at laser powers of 60 W and 80 W with laser traverse speeds of 150, 200, and 250 mm/min.

4.2 Relationship of Laser Traverse Speed and Laser Power

Section 4.1 illustrated that laser power and laser traverse speed had the greatest influence on channel creation and size. The combination of those two parameters was responsible for the channel uniformity, rate of surface penetration and hence the channel width, due to the amount of heat generated in the material [24].

In general, in a laser cutting process an increase in laser power implies that working at faster speeds and achieving greater cut depths is possible. The disadvantage is that wider widths may be unavoidably achieved and cut quality may suffer [18].

To analyse the effects of laser power and laser traverse speed in a more detailed way, a test was conducted varying only the laser power, in a greater than previous range (50 W to 180 W), and the laser traverse speed (between 50 mm/min and 300 mm/min in steps of 50 mm/min). The gas flow rate was kept constant throughout the testing period (20 l/min). Figures 13 and 14 show the relationship of laser power and laser traverse speed on channel and shoulder width and the inner channel width respectively. As can be seen in Figure 13, an increase in laser power resulted in a greater cut width of up to 480 µm at a laser traverse speed of 300 mm/min. Consequently, all laser traverse speeds
demonstrated the same behaviour, namely that an increase in laser power increased the cut width achieved. Excessive laser powers resulted in larger widths which were unfavourable in this current project – a wide zone affected leads to a decrease of possible channel numbers being generated next to each other thus reducing the ability to embed a high volume fraction of fibres. Figure 14 shows the affected width of the inner channel which was several factors smaller than the outer channel and shoulder region. A low input laser power and a slow laser traverse speed did not create a channel at all. The channel creation initialised at a laser power of 110 W suggesting a higher energy density to be necessary to sufficiently penetrate the material. Only at higher laser traverse speeds, above 150 mm/min, were channels created. The majority of the inner channel widths lay within the diameter range of 50 µm and 100 µm which was favourable in terms of the intended fibre embedding and allowed variation of channel widths for different fibre diameters and types. In accordance with section 4.1 higher laser powers were needed to achieve greater penetration and cut width increases.

The reason for insufficient channel creation at lower laser powers was due to the reduction in laser power density, which was the power per square unit of area. Due to the profile of the laser beam being Gaussian the laser power was not linearly distributed, therefore the power density value was an average across the spot size area [18]. The result of reduced power density was less energy transferred to the Al-alloy surface, and less heat was conducted, therefore less material was melted resulting in a smaller melt pool and ultimately a smaller degree of laser processing/cut size. A linear relationship between laser power and laser traverse speed can be seen in Figure 14 [18, 22].

4.3 Channels for High Volume Fractions of Fibres

The laser/material interaction could be controlled in the desired manner and so the next step was to create multiple channels along the length of a UC processed sample. Microscopic inspection of the samples from sections 4.1 and 4.2 revealed that the Heat Affected Zone (HAZ) of the Al alloy material extended in the z-direction but not in the x and y direction. This has been noted by others [19, 24, 25], who also identified that the HAZ was narrow and parallel with the weld bead created by the laser. No obvious metal melting happened in the HAZ during laser processing. Figure 15 shows a laser created channel in the Al alloy material with its HAZ. The HAZ was dependent on the laser power and laser traverse speed which was also noted by Singh [26]. Section 4.2 showed that parameters for channels suitable for the purpose of this study were located in the range of relatively higher laser traverse speeds and laser powers.

It was envisaged that to exploit the full potential of smart materials a high volume of fibres as well as a combination of different fibre types must be embedded. To date research has been carried out embedding three to ten fibres in an aluminium matrix [2, 3]. Since the HAZ and the channel shoulders did not significantly influence the width between the channels, it was concluded that a pattern allowing the creation of many channels could be generated within one UC processed sample. The consolidated samples that were laser processed had a width of 24 mm and a length of 200 mm. Laser processing was carried out by cutting channels in both the horizontal and vertical direction as there was no identified influence of the laser traversing direction on the success of channel creation. Another reason for using both the horizontal and vertical directions was that during UC fibres may be integrated horizontally or vertically depending on the type of sample being built.

The diameter considered for the fibres lay in the range of 50 µm to 100 µm. Therefore a maximum diameter of 100 µm for the laser channels was considered to be suitable for the present work. Analysis of the available UC processed surface area allowed the calculation that a maximum of 32 laser channels could be realised during laser processing without an interference of two adjacent channels in the horizontal direction. In the vertical direction the number of possible channels was far greater due to the samples length of 200 mm compared to a sample width of 24 mm.

Figure 16 shows 16 channels processed within one sample post UC processed Al sample by the fibre laser. The channels had a length of 20 mm. The area covered by the chanelling was 217.5 mm². Analysis was conducted using a white light interferometer to produce detailed topological analysis of the surface and channels of the Al samples. Figure 16 shows that the samples underwent some
distortion while laser processing causing a bowing of the Al sample. This distortion was attributed to a relatively high heat input when creating a higher number of channels within a relatively small area and onto a thin Al sample. A vacuum chuck was used to hold the samples in place during laser processing however there were issues with holding the sample flat, leading to varying widths and depths during channel creation. The channels were successfully created without interfering with each other however analysis of the channel depth was found to be greater in the centre of the sample (50 µm to 100 µm), whereas the surrounding area had penetration depths of down to 0 µm. As the whole sample was apparently under the influence of bending it was considered that every area would have to be calculated and measured with the right bending angle and thus interferometer compensation could be introduced. It was also apparent that the depth along the length of the channels was not constant with depths of channels ranging from 100 µm to 0 µm. Further investigation identified that the reason for this variation, even with bend angle compensation, was that the post UC surface of the Al sample was highly roughened due to sonotrode contact. Figure 17 shows the surface of a post UC processed Al alloy surface with a measured average surface roughness of between 0 to 20 µm. The effect of this uneven surface on laser processing is that the absorption of the laser energy is different at every point of the surface leading to different penetration rates [17]. The effect of laser power, laser traverse speed and gas flow rate within the cut prepared by a laser has been investigated by many other authors [1, 24, 27, 28].

Figure 18 depicts a series of profiles throughout a 16 channel laser processed Al alloy section. This allowed the analysis of how channels behave along the whole channel length of 20 mm. The diagram reveals that all 16 channels had an average depth of approximately 100 µm. The width of the channels was approximately 100 µm to 150 µm.

5. SUMMARY AND CONCLUDING REMARKS

Ultrasonic Consolidation is a solid state metal layer manufacturing process that operates by ultrasonically welding a sequence of thin metal foil layers together and then using CNC machining to create a three dimensional geometry direct from a computer generated model. A phenomenon known as ‘acoustic softening’ is encountered during UC which can be exploited to embed sensitive objects between the foil layers, mid process, and thus allow for the creation of smart metal matrix composites. There were limits on the volume fraction of fibres/objects possible using the current method of fibre placement and thus an alternative of pre machined channels of the foil material had been proposed and initially explored in the present work.

This initial study had shown that it is possible to create laser cut channels on the surface of a post UC processed Al 3003 H18 sample and that these channels were of a partially controllable nature. In addition to the channels this initial work identified the creation of a ‘shoulder’ feature on the edge of the laser cut channels which was postulated to be of benefit with regards to reducing the volume of plastic flow required during UC processing to embed higher volume fractions of fibres. A HAZ was identified at the base of the created channels post laser processing as a result of the heat generated during the laser/material interaction.

Difficulties arising from the highly uneven nature of the post UC sample surface have been identified with regards to accurate laser cutting and these difficulties have led to issues of non-uniformity of both the width and depth of the created channels. To what extent this plays a role in further processing and especially in secure and complete fibre integration will be investigated in the near future as will the microstructural and processing effect of the HAZ.

The embedding of a range of fibre types and geometries using UC and foils that have been channelled via the laser processing will be performed in the future and the effect of this on fibre volume fractions, UC sample strength and fibre placement accuracy will be assessed using a range of mechanical and imaging analysis.
The purpose of this work was to further the advancement of UC towards creating fully integrated smart metal matrix composites.

REFERENCES


Figure 1: Schematic 1 of the Ultrasonic Consolidation material deposition equipment
Figure 2: Schematic 2 of the Ultrasonic Consolidation material deposition equipment

Figure 3: Schematic of the Ultrasonic Consolidation manufacturing process and foil/component bond interface
Figure 4: Schematic of the Ultrasonic Consolidation object embedding process

Figure 5: Images showing a range of different embedded objects via Ultrasonic Consolidation
Figure 6: µCT image showing fibre movement in a post processed Ultrasonic Consolidation component

Figure 7: Schematic of fibre embedding during Ultrasonic Consolidation: (a) as conventional processing, (b) with new channel feature
Figure 8: Schematic of envisioned laser channel production

Figure 9: Schematic of the setup for fibre laser processing
Figure 10: Image of a typical channel created on the surface of the post-Ultrasonic Consolidation processed foil

Figure 11: Effect of laser power, laser traverse speed and gas flow rate on created channel width
Figure 12: Inner channel width for various laser traverse speeds, laser powers and gas flow rates

Figure 13: Relationship of laser traverse speed and laser power on combined channel and shoulder width

Figure 14: Relationship of laser traverse speed and laser power on inner channel width
Figure 15: Micrograph showing the heat affected zone of a processed laser channel created using air as a shroud gas.

Figure 16: a) Topography of 16 laser channels on the post Ultrasonic Consolidation processed Al 3003 H18 alloy surface and b) 3D view of the 16 channels.

Figure 17: 3D topology of post Ultrasonic Consolidation processed Al 3003 H18 foil.
Figure 18: Diagram of a laser processed Al 3003 H18 sample cross section showing 16 channels