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Bond formation and fiber embedment during ultrasonic consolidation

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ABSTRACT

The quality of ultrasonically consolidated parts critically depends on the bond quality between individual metal foils. This necessitates a detailed understanding of interface microstructures and ultrasonic bond formation mechanisms. In this work, the interface microstructures of a variety of ultrasonically consolidated similar and dissimilar metal samples were investigated. Samples with embedded SiC fibers were also investigated. Based on detailed microstructural studies, the mechanisms of foil bonding and fiber embedment in ultrasonic consolidation have been discussed.

1. Introduction

Ultrasonic consolidation (UC) is a novel additive manufacturing process implementing ultrasonic metal welding for fabrication of complex three-dimensional (3D) structures from metal foils. The Solidica Formation^{TM} UC machine (commercially introduced by Solidica Inc., USA, in 2000) incorporates an ultrasonic metal welding head, a 3-axis CNC milling head, a foil feeding apparatus, and a software program to automatically generate tool paths for material deposition and machining. In the UC process, a CAD model of the component to be fabricated is initially generated. The model is converted to an STL file format and systematically sliced into a number of horizontal layers using a customized computer program. Each horizontal layer corresponds to the thickness of the metal foil used for part fabrication. Fig. 1 illustrates the basic UC process. A rotating ultrasonic welding head, a.k.a. sonotrode, travels along the length of a thin metal foil placed on a base plate. The foil is held closely in contact with the base plate by applying a normal force via the rotating sonotrode. The sonotrode vibrates transversely to the direction of travel at a frequency of 20 kHz and at a user-set oscillation amplitude, while traveling over the metal foil to bond it to the base plate. After depositing a strip of foil, another foil could be deposited adjacent to it depending on the geometry of the part. This operation repeats until a complete layer is placed. After placing a layer, a CNC milling head subtractively shapes the layer to its slice contour. This milling can occur after each layer or after several deposited layers. After shaping a layer, machining chips are blown away using compressed air and foil deposition starts for the next layer. These additive and subtractive operations repeat until the component is finished.

Research on the practical applications of UC has been extensive. Previous work has demonstrated the unique capabilities of UC for fabrication of multi-functional 3D structures with high dimensional accuracy and desirable surface finish. George (2006) has demonstrated honeycomb panels with complex internal features, Janaki Ram et al. (2007a) have made multiple material structures, and Siggard (2007) has fabricated objects with integrated wiring and electronics.

Another interesting application of UC is embedding fibers within metal matrices for producing metal matrix composites (MMCs) and for other purposes. A variety of fibers have been successfully embedded in aluminum matrices. Yang et al. (2007) have successfully embedded silicon carbide (SiC) fibers within Al 3003, and Kong (2005) reported similar successes on shape memory alloy and optical fibers using UC.

Although the application potential of UC has been widely investigated, the mechanism of bond formation between metal foils during UC has not been clearly understood. Since the additive operation during UC is essentially a seam ultrasonic metal welding (UMW) application, an improved understanding of bond formation in UC can be obtained from the available information on bond formation in UMW. As discussed by Jones and Powers (1956) it is generally agreed that ultrasonic metal welding is a solid-state joining process. Apart from pure solid-state bonding, which is caused

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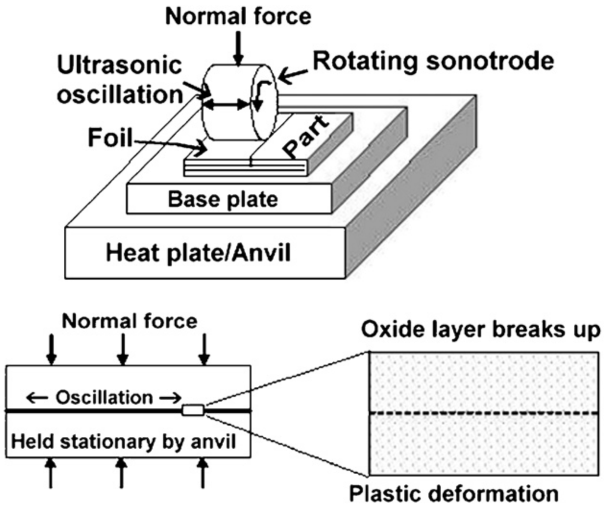

Fig. 1. Schematic of ultrasonic consolidation process (not to scale).

by atomic-level forces across nascent metal contact points, bond formation during UMW has been suggested by Joshi (1971) to be due to: (i) mechanical interlocking, (ii) interfacial melting, and (iii) metal diffusion. While all these mechanisms can contribute to bond formation, the operating or the dominant mechanism is expected to change with the materials in question and with the processing conditions. Therefore, it is important to know which mechanisms dominate under standard UC processing conditions. The current lack of consensus on foil bonding mechanisms in UC limits further exploitation of its processing capabilities.

In view of the above, an attempt is made in this work to investigate bond formation during UC using a variety of ultrasonically consolidated similar and dissimilar metal samples. Further, an attempt is made to understand the mechanism of ceramic fiber embedment during UC.

2. Experimental details

2.1. Ultrasonic consolidation of Al 3003 and Ni 201

Metal tapes used in the current study are listed in Table 1. No special foil cleaning procedures were adopted to facilitate bonding. UC experiments were conducted using a Solidica Formation^{TM} machine with a sonotrode diameter of 147 mm. Metal foils were deposited onto an Al 3003 base plate firmly bolted to the heat plate of the UC machine. The procedure for depositing Al 3003 tapes involved first depositing a layer of Al 3003 on the aluminum base plate. Subsequently, another layer of Al 3003 was deposited on the top of the previously deposited Al 3003 layer. The Al 3003 tapes were automatically fed through the tape feeding mechanism of the UC machine. The processing parameters used for Al 3003 foil consolidation were: oscillation amplitude, 16 μm; welding speed, 28 mm/s; normal force, 1750 N; and base plate temperature, 149 °C. These parameters were found by Janaki Ram et al. (2007b) to produce a high level of linear welding density for Al 3003.

A similar procedure and processing parameters were implemented for depositing Ni 201 metal tapes. Since Ni 201 tapes were not available in standard coils suitable for automatic feeding by the machine, tapes were manually placed onto the base plate and secured with an adhesive at the ends, followed by welding.

Table 2
Process parameters used for SiC fiber embedment.

Parameter	Value	
	Al 3003/SiC/Al 3003	Al 3003/SiC/Cu
Vibrational amplitude (μm)	10	12
Normal force (kPa)	275	275
Welding speed (mm/s)	28	28

2.2. Ultrasonic consolidation of dissimilar metal foils

Dual-material samples were fabricated from Al 3003 and Ni 201 tapes. Here again, deposition experiments were conducted using the Solidica Formation^{TM} machine on an Al 3003 base plate. After depositing a few layers of Al 3003 one over another, a layer of Ni 201 was welded to the top most Al 3003 layer. Subsequently, another layer of Ni 201 was welded to the previously deposited Ni 201 layer. This layer arrangement was chosen to facilitate microstructural examination of Ni–Al and Ni–Ni interfaces. As before, Ni tapes were manually placed onto the substrate and secured with adhesive while Al 3003 layers were automatically fed. The process parameters were identical to those used for ultrasonic consolidation of Al 3003.

2.3. SiC fiber embedment

The fiber embedment experiments were conducted using an ultrasonic seam welder at Loughborough University, UK, with a sonotrode diameter of 50 mm. This machine is as capable as the commercial UC machine in terms of joining thin metal foils. Manually fed 100 μm thick foils were used and no base plate preheating was employed in all the experiments conducted using this machine.

Silicon carbide fibers of 100 μm diameter were embedded between Al 3003 foils along their length, following the embedding procedure described by Yang et al. (2007), who successfully embedded SiC fibers within Al 3003 matrices using this procedure. In order to understand the effects of foil material properties on fiber embedment, SiC fibers were embedded between Al 3003 foil and high-purity Cu (99.9%) foil of 100 μm thickness. The process parameters used for these experiments are listed in Table 2.

2.4. Microstructural characterization

Ultrasonically consolidated similar and dissimilar metal samples as well as fiber embedded samples were metallographically investigated. Transverse sections (perpendicular to the foil length direction) cut from the various samples were prepared for microstructural examination following standard metallographic practices. Some of the Al 3003 samples and fiber embedded samples were etched with Keller's solution (HF-1%, HCl-1.5%, HNO_3-2.5%, and H_2O-95%). Ni 201 samples were etched with a mixture of 1 part 10% aqueous solution of CaCN and 1 part 10% aqueous solution of $(NH_4)_2S_2O_8$. Metal/metal and fiber/metal interface microstructures were examined using a scanning electron microscope (SEM). X-ray energy dispersive spectroscopy (EDS) was utilized for micro-

Table 1
Materials used for UC experiments.

Material	Nominal composition (wt.%)	Dimensions
Al alloy 3003 (H18 condition)	Al–1.2Mn–0.12Cu	25 mm wide, 150 μm thick foil
Ni alloy 201 (annealed condition)	Ni–0.02C–0.35Mn–0.25Si–0.25Fe–0.15Cu	25 mm wide, 75 μm thick foil