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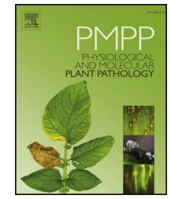

Ultrasonic Additive Manufacturing as a form-then-bond process for embedding electronic circuitry into a metal matrix

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ABSTRACT

Ultrasonic Additive Manufacturing (UAM) is a hybrid manufacturing process that involves the layer-by-layer ultrasonic welding of metal foils in the solid state with periodic CNC machining to achieve the desired 3D shape. UAM enables the fabrication of metal smart structures, because it allows the embedding of various components into the metal matrix, due to the high degree of plastic metal flow and the relatively low temperatures encountered during the layer bonding process. To further the embedding capabilities of UAM, in this paper we examine the ultrasonic welding of aluminium foils with features machined prior to bonding. These pre-machined features can be stacked layer-by-layer to create pockets for the accommodation of fragile components, such as electronic circuitry, prior to encapsulation. This manufacturing approach transforms UAM into a "form-then-bond" process. By studying the deformation of aluminium foils during UAM, a statistical model was developed that allowed the prediction of the final location, dimensions and tolerances of pre-machined features for a set of UAM process parameters. The predictive power of the model was demonstrated by designing a cavity to accommodate an electronic component (i.e. a surface mount resistor) prior to its encapsulation within the metal matrix. We also further emphasised the importance of the tensioning force in the UAM process. The current work paves the way for the creation of a novel system for the fabrication of three-dimensional electronic circuits embedded into an additively manufactured complex metal composite.

1. Introduction

Ultrasonic Additive Manufacturing (UAM) is a hybrid sheet lamination/Computer Numerical Control (CNC) manufacturing process. UAM utilizes Ultrasonic Welding (UW) to bond thin metal foils in a layer-by-layer fashion and periodic CNC machining to create the desired 3D shape. The technology was first introduced by White [1] under the name of Ultrasonic Consolidation. During the bonding step, a cylindrical textured machine tool, called the sonotrode, is pressed at a constant normal force against the metal foil, which is kept in place via a clamping or tensioning mechanism. The sonotrode rolls over the foil while oscillating at a constant frequency of approx. 20 kHz perpendicular to the direction of travel (see Fig. 1). This results in the creation of a solid state bond between the interfaces of the foil and the metallic substrate. The process is then repeated until the desired height is reached.

The quality of bonding during UAM depends on multiple processing and material parameters, however, the three main process parameters are the sonotrode's amplitude of oscillation [μm], the sonotrode exerted normal force [N], and the linear speed [mm/s] of the sonotrode. The effect of each of these processing parameters was closely examined for the first time by Kong et al. [2], who identified that an optimum set exists past which degradation of the previously formed bonds occurs. More recent studies by Hopkins et al. [3] and Wolcott et al. [4] identified the amplitude and weld speed as the most significant parameters for creating high-quality bonds in UAM of aluminium alloys.

Bonding in UAM occurs at a relatively low temperature. This was measured by Kelly et al. [5] using an infrared camera and higher amplitudes of oscillation ($> 25\,\mu m$) and Schick et al. [6] and Sriraman et al. [7] by embedding thermocouples in the foil-foil interface at lower amplitudes ($< 25\,\mu m$). All three studies reported a peak temperature considerably lower than the melting point of aluminium (under 250 °C in the first case and less than 100 °C in the later cases) that dissipates rapidly away from the bonding interface. Moreover, a relatively high degree of plastic metal flow is induced during ultrasonic bonding, which has been studied extensively by Kong et al. [8] and Yang et al.

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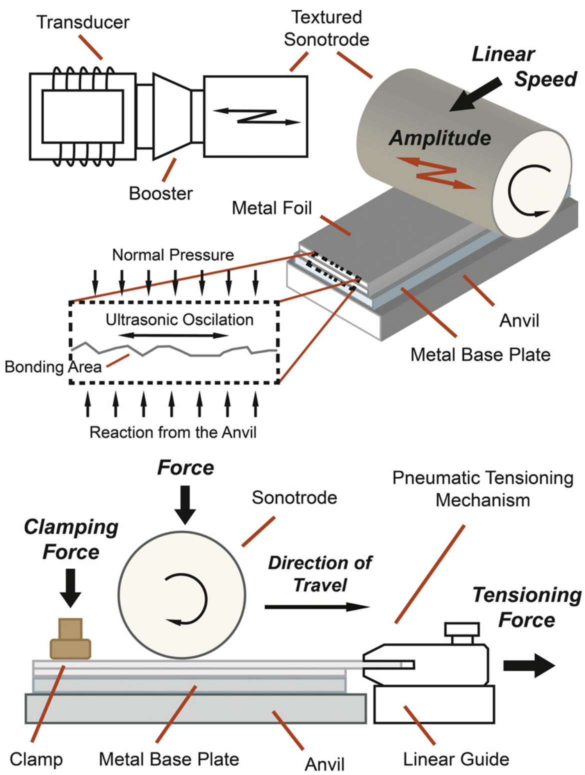

Fig. 1. Schematic overview of Ultrasonic Additive Manufacturing (UAM).

[9] using different machine setups. Both researchers concluded that an increase in the amplitude of oscillations promotes the plastic metal flow due to mechanisms, such as the acoustic softening phenomenon.

These unique properties of UAM have been exploited in the past allowing the embedding of various electronic structures into a metal matrix. For example, Li et al. [10] reported the embedding of printed electronic pathways directly between the aluminium foil interfaces and Siggard et al. [11] and Robinson et al. [12] encapsulated pre-packed electronic circuitry and printed electronic pathways respectively in CNC machined substrate pockets. Moreover, metal matrix composites have been successfully manufactured using UAM. For example, Kong and Soar [13] have successfully embedded polymer-coated and uncoated optical fibres in an aluminium matrix, while similar work has been carried out by Monaghan et al. [14] and Mou et al. [15] for embedding metal-coated optical fibres and Bragg fibres respectively. Shape memory alloy fibres have been embedded in aluminium using UAM by Friel and Harris [16] and Hahnlen and Dapino [17] fabricated an active metal matrix composite in a similar fashion using NiTi fibres. In each of the aforementioned studies, the researchers reported good functionality of the embedded components and very good bond strength in the welded interfaces of the metal foils and thus UAM is considered an enabler for the fabrication of smart metal structures.

After UAM bonding several layers, a CNC machining step is introduced to give the desired form to the bonded metal foils. The cycle of bonding metal foils onto the previously fabricated and formed part and machining the newly bonded layers to shape is repeated until the part is complete. For this reason, Gibson et al. [18] categorised UAM as a "bond-then-form" process in their review of the sheet lamination technologies.

An alternative methodology for creating 3D objects through a sheet lamination process is the "form-then-bond" approach [18]. In this approach, the desired shape is given to each layer (e.g. via razor cutting, or laser machining) prior to bonding it to the previously fabricated part. This enables the creation of structures with internal features and channels, which are more difficult to manufacture with a bond-then-form methodology. The benefits of this approach have been demonstrated by Cawley et al. [19], who successfully manufactured functional ceramic components and microfluidic devices using the Computer-Aided Manufacturing of Laminated Engineering Materials (CAM-LEM) method, and by Thabourey et al. [20], who developed a methodology for the manufacturing of die casting moulds with internal cooling channels.

UAM has previously been shown capable of embedding electronic components such as sensors and antennas as shown by Siggard et al. [11] and Robinson et al. [12] respectively. Moreover, 2D printed electronic pathways were embedded directly between the foil-foil interfaces by Li et al. [10]. However, new more compact electronic designs rely on a 3D architecture with vertical vias connecting each layer electrically. Traditional UAM requires milling or drilling to connect subsequent layers, which can risk damaging underlying electronic components. Moreover, metal chips and lubricant can create short circuits. On the other hand, the form-then-bond method allows for prefabricated vias with no need for further post-processing. A form-then-bond approach would also enable the preparation or pre-treatment (chemical, mechanical or other) of the metal foils prior to bonding. For example, the planar surfaces of aluminium foils and the vertical inner walls of machined features on these foils could be selectively anodized prior to bonding. This way an electrically insulating layer is created onto which planar and vertical electronic interconnects can be deposited and then embedded in creating 3D electronic circuits. This method was examined in a previous article by the author [21], demonstrating its feasibility and limitations, as well as the effect of the ultrasonic power on the resistivity of printed conductive materials [37]. Alternatively, printed electronic interconnects and other electronic circuits (e.g. RFID antennae) could be deposited or attached to the surface of an aluminium foil prior to UAM, which could then be bonded onto a metal substrate, encapsulating the circuit. These novel approaches could provide greater manufacturing capabilities for embedding electronics into a metal matrix and produce components that have direct applications into growing industries, such as the Internet of Things.

By taking advantage of the benefits of the form-then-bond approach, the authors have envisioned an alteration to the traditional UAM manufacturing process, which is illustrated schematically in Fig. 2. In

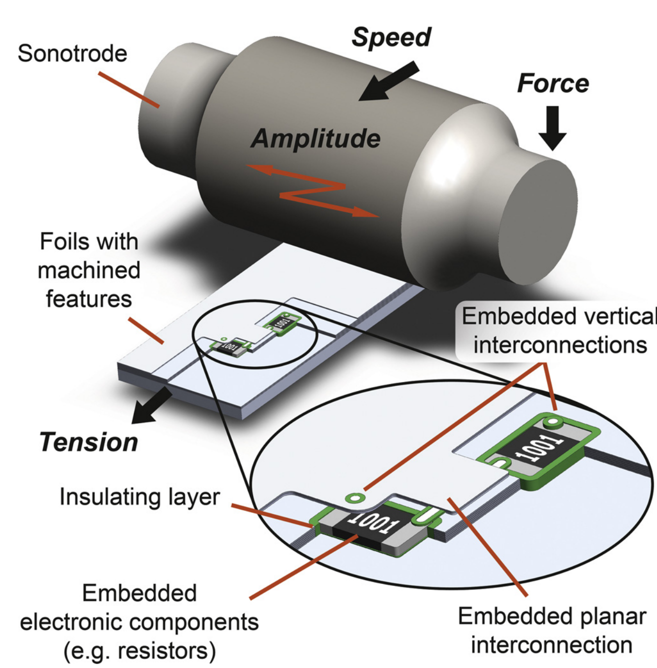

Fig. 2. Illustration of electronic circuitry embedded in a metal matrix using the proposed approach.