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Bournias-Varotsis, Alkaios, Ross J. Friel, Russell A. Harris, and Daniel S. Engstrom. 2019. “Selectively Anodised Aluminium Foils as an Insulating Layer for Embedding Electronic Circuitry in a Metal Matrix via Ultrasonic Additive Manufacturing”. figshare. https://hdl.handle.net/2134/23678.

Solid Freeform Fabrication 2016: Proceedings of the 27th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

SELECTIVELY ANODISED ALUMINIUM FOILS AS AN INSULATING LAYER FOR EMBEDDING ELECTRONIC CIRCUITRY IN A METAL MATRIX VIA ULTRASONIC ADDITIVE MANUFACTURING

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Abstract

Ultrasonic Additive Manufacturing (UAM) is a hybrid Additive Manufacturing (AM) process that involves layer-by-layer ultrasonic welding of metal foils and periodic machining to achieve the desired shape. Prior investigative research has demonstrated the potential of UAM for the embedding of electronic circuits inside a metal matrix. In this paper, a new approach for the fabrication of an insulating layer between an aluminium (Al) matrix and embedded electronic interconnections is presented. First, an Anodic Aluminium Oxide (AAO) layer is selectively grown onto the surface of Al foils prior to bonding. The pre-treated foils are then welded onto a UAM fabricated aluminium substrate. The bonding step can be repeated for the full encapsulation of the electronic interconnections or components. This ceramic AAO insulating layer provides several advantages over the alternative organic materials used in previous works.

1. Introduction

Ultrasonic Additive Manufacturing (UAM) – also known as Ultrasonic Consolidation – is a hybrid manufacturing process that is based on the layer-by-layer bonding of metal foils via ultrasonic welding and the periodic CNC machining to achieve the desired shape [1]. The welding process is outlined in figure 1. For the application of the ultrasonic oscillation a textured cylindrical sonotrode is utilized, which rolls over the length of the metal foil and applies a compressive normal force. Bonding occurs in the solid state [2] and at relatively low temperatures (< 150^{o}C) [3]. The absence of high temperatures, allows the embedding of electronic circuitry in the metal matrix. This has been successfully demonstrated by prior investigative research [4]–[6]. Nevertheless, a process that allows the freeform embedding of compact 3D circuitry has not yet been realized.

A key challenge that hinders progress towards this goal is the development of an effective methodology for the deposition of the insulating layer between the electronic components and the metal matrix. Past research [4]–[6] focused on using organic materials for this purpose. In this paper we examine the suitability of Anodic Aluminium Oxide (AAO) layers that were selectively anodised onto aluminium metal foils prior to the ultrasonic welding.

Anodising is a well-known, cost-effective surface treatment technology, which allows the growth of a porous AAO layer on the surface of aluminium specimens [7]. In this process, the specimen is submerged in an electrolytic solution, consisting of a diluted acid (typically sulfuric, phosphoric or oxalic), and an electric potential is applied between the specimen and a cathode. This results in the rapid oxidation of the surface of the specimen and the creation of a porous ceramic coating. The layer and porosity of the created AAO layer can be controlled by adjusting the process parameters, such as the anodization time, the current density, the type and

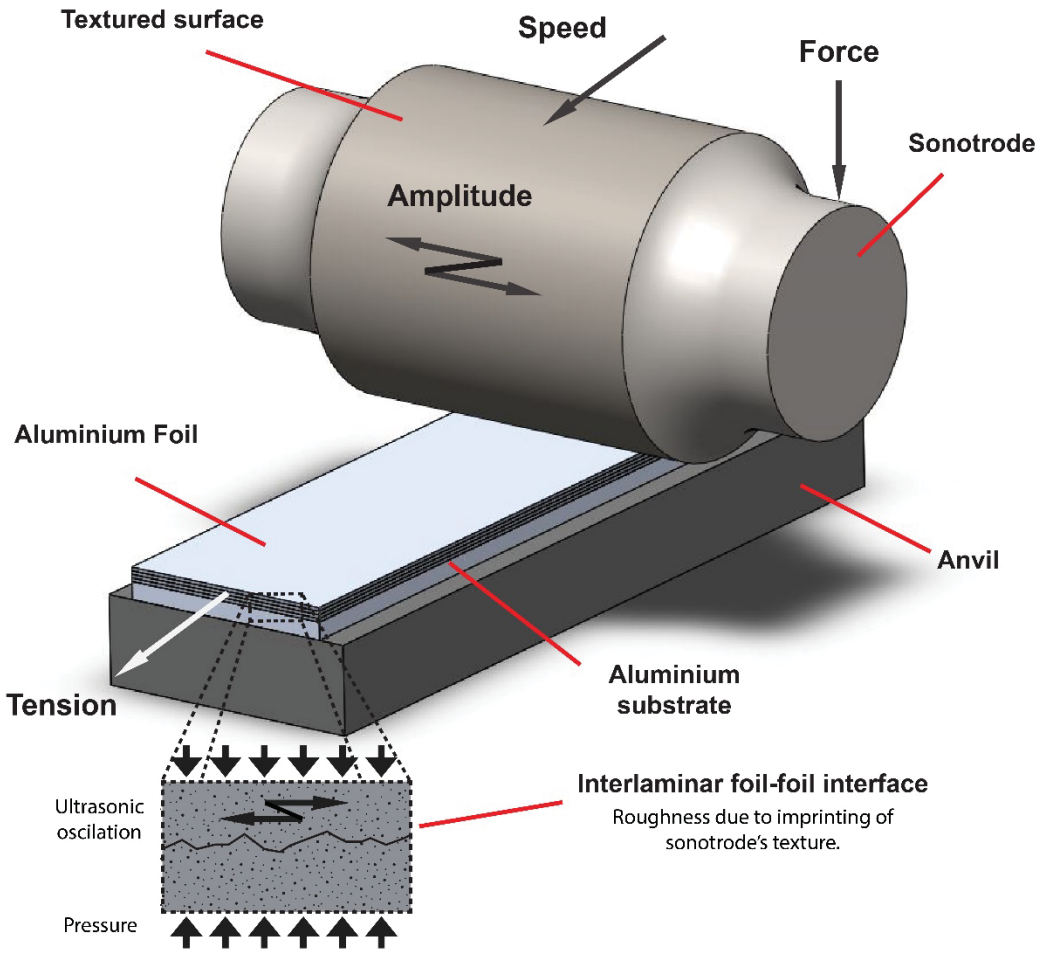


Figure 1: Overview of the UAM process

concentration of the electrolyte and the temperature of the solution [8]. Various masking techniques can be used to protect the areas of the specimens that we do not wish to be anodised. The porosity of the film can be reduced through a post-processing step called sealing, which involves exposure of the AAO to an aqueous environment at elevated temperatures (over 80^{o}C), usually by submerging the specimens in near boiling water or in an ionic solution [9].

Anodic coatings have proved to be suitable substrates for both thick film and thin film electronic manufacturing applications, since they exhibit excellent insulating properties, high thermal conductivity and wettability [10], [11]. Moreover, the excellent mechanical properties of the AAO (i.e. very high hardness and abrasion resistance) indicate that the anodic coating can withstand the high mechanical loads developed during UAM process. Nevertheless, the brittleness and the low shear strength of the AAO layer need to be taken into consideration.

2.5D circuits have been successfully fabricated in the past by selectively anodising aluminium sheets with pre-drilled vertical via [12]. In our proposed methodology, the aluminium foils are first machined, mechanically and chemically, to create cavities for the embedding of the electronic circuitry and are subsequently anodised and bonded onto an aluminium substrate using

UAM. The foils prepared this way can be stacked accordingly to create cavities for the placement of the electronic components and interconnections. We have demonstrated the potential use of UAM as a form-then-bond process in a previous work [13].

In this paper we present the results of the early stage research on the compatibility with the UAM process of selectively anodised aluminium foils. First we describe the potential benefits of the proposed manufacturing process. Then the results from this initial investigative research are presented and shortcomings in the followed methodology are discussed.

2. Process Overview

UAM was originally designed as a bond-then-form process, meaning that each new material layer is bonded to the previous layer prior to be given the desired shape through the CNC machining step [14]. This method posed limitations when depositing the insulating material between the metal matrix and the electronic circuitry. Previous researchers have achieved that by repeated CNC milling and deposition and curing of insulating resin [5]. The above approach might case issues when the embedding of sensitive components is desired: dimensional and positional inaccuracies and poor alignment can place the embedded components in a toolpath [15]. This effect is more prominent when the height of the embedded components is larger than the layer height, as is often the case with electronic circuitry (the typical foil thickness used with UAM is between 100 to 200 μm). In another past study, dielectric and conductive material was screen printed onto the surface of a UAM fabricated aluminium substrate and then directly encapsulated between the layers of the foil-foil interface [6]. Even though promising results were obtained, the height of the embedded circuitry is limited to a maximum critical height (approx. 40 μm). Also the creation of vertical interconnections could not be easily achieved.

In order to overcome the limitations of the bond-then-form methodology, we examine the possibility of depositing the insulating layer onto the foil prior to UAM bonding. Anodic aluminium oxide was selected as the insulator for the advantages described above, but also because AAO coating grows on all exposed aluminium surfaces, even vertical walls. This way vertical interconnections can be easily created, by machining or drilling slots or through hole via on the aluminium foils prior to anodising [12].

We examined this possibility by preparing samples with embedded interconnections using the structure that is illustrated in figure 2. Three types of foils were prepared: the foil of the first layer was selectively anodised only on one side, while the foils of the second and third layer were selectively anodised on both sides. The second and third layers were also machined prior to anodising to create channels and through hole via for the placement of a silver conductive paste for the creation of the conductive track. Prior to anodising and after any machining, all three foils were electropolished in a concentrated acid solution at elevated temperature. Preliminary experimentation showed that the electropolishing step was necessary: the AAO layer grows in both directions, creating a protruding formation that has a step height of approx. 50% of the total thickness of the AAO layer above the surface of the foil [7]. During UAM bonding, this protruding formation was destroyed by the sonotrode and this resulted into a rough surface and cracks. Also the electropolishing step contributed to the removal of any contaminants and the smoothing of the edges after machining. The foil preparation process is graphically summarised in figure 2 and it will be described in detail in the next section. Three samples were prepared and tested for this preliminary study.

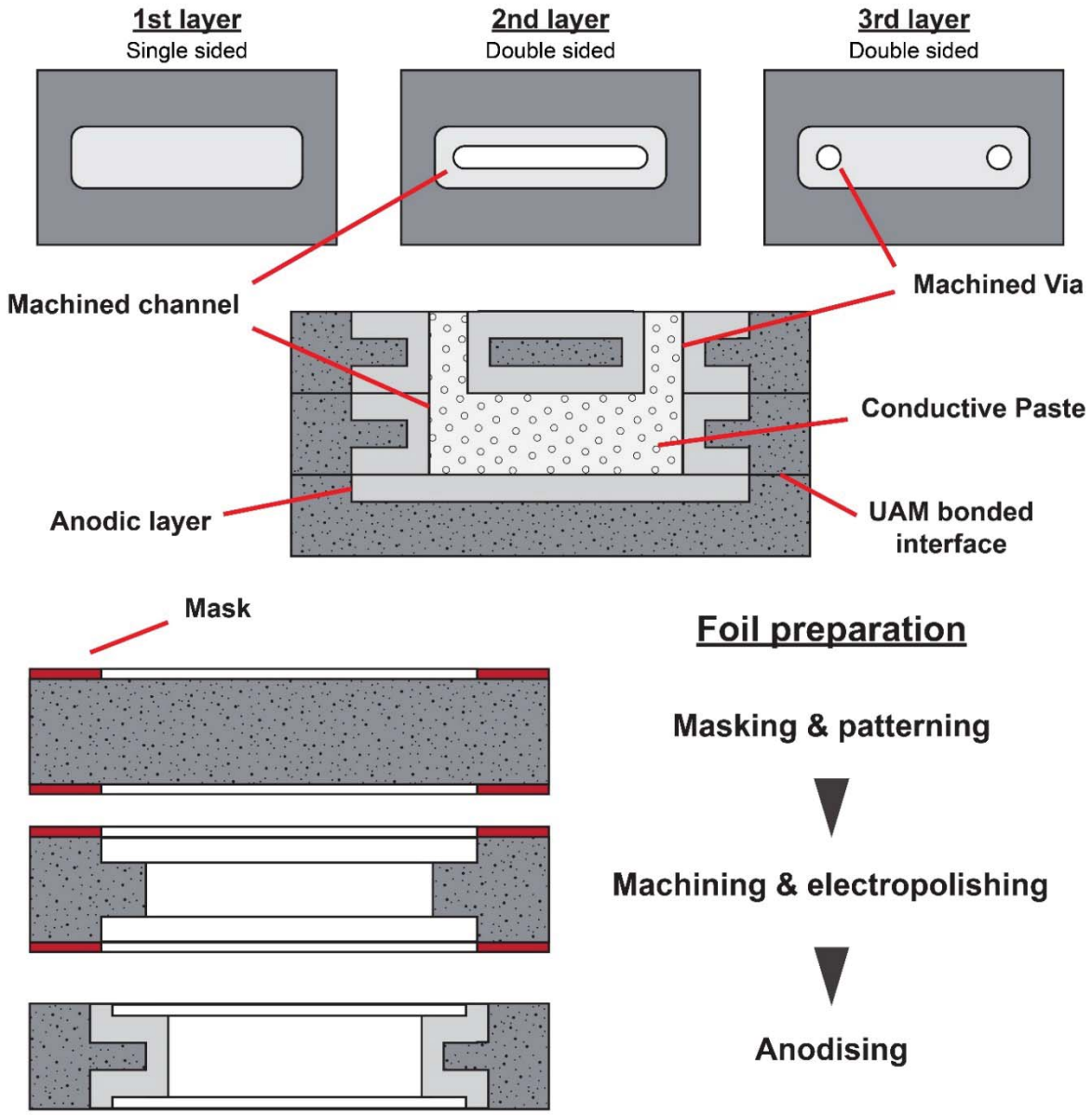


Figure 2: Illustration of the fabricated samples and overview of the selectively anodised foil preparation process

3. Experimental methodology

3.1 Substrate preparation

The Alpha 2 UAM machine (Solidica Inc., USA) was used for the preparation of all the samples of this study. This consists of a 3kW ultrasonic seam welder operating at a constant frequency of 20kHz. Substrates were prepared by ultrasonically welding two 100 μm thick and 24 mm wide Al 3003-H18 foils onto a 1.2 mm thick Al 1050-H14 baseplate. The level of UAM parameters used for the preparation of the substrate were 1600 N for the normal force, 30 mm/s for the linear speed and 18 μm for the amplitude of vibrations. This is a set of parameters that has been proven to produce excellent welding results [13].

3.2 Preparation of selectively anodised foils

Aluminium alloy foils, identical to the foils used for the substrate preparation (100 μm thick, 24 mm wide Al 3003-H18 foils), were masked and patterned, machined and electropolished and then selectively anodised.

Masking and patterning: The foils were first cut to length (approx. 20 cm long) and degreased using an industrial detergent prior to masking. Two layers of a chemically resistant stop-off lacquer (Miccroshield, Hi-Tek Products Ltd) were applied by deep coating and left to air dry. A CO_2 laser marker was used to create a 50 mm long and 4.8 mm wide pattern along the centre axis of the masked foils. Both sides of the foils were pattern when necessary.

Machining and electropolishing: Channels (20 mm long by 1 mm wide) and through hole via for the placement of the conductive paste were then machined on the foils using a manual milling machine with a 1 mm cutting tool head. The prepared foils were then degreased using acetone and a warm (40°C) alkaline bath and subsequently electropolished in a mixture of acids (66% wt. phosphoric acid, 15% wt. sulfuric acid, 3% wt. ethylene glycol) at 80°C for 2 minutes [7]. This resulted in the removal of approx. 20μm of material.

Selective anodising: The foils were anodised in a 15% wt. sulfuric acid solution at constant current. Anodising with constant current was preferred over constant voltage anodising, because it allows for the closer control of the process [7]. In order to determine the necessary anodising time and current density to create an AAO layer with the desired thickness, a series of experimental runs were conducted, the results of which are summarised in figure 3. The target thickness was set to 30 μm, to generate a thick enough, yet flexible insulating layer [12]. For this reason, the prepared foils were anodized for 30 minutes at 30 mA/cm^2 constant current density.

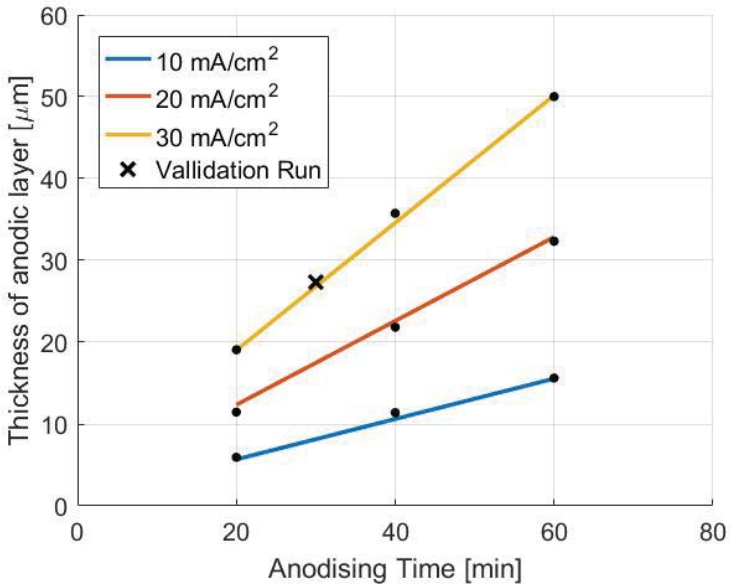


Figure 3: Thickness of the Anodic Aluminium Oxide layer for variable anodising time and current density

3.3 UAM bonding

The prepared selectively anodised foils where then ultrasonically welded onto the prepared substrates using the UAM equipment. Three different bonding techniques were tested. The first sample was prepared using the standard UAM process, using the same set of parameters as for the substrate preparation. For the second a third samples, a variation of the standard technique was utilised: a series of spot welds were made along the whole length of the sample, by placing the sonotrode over the top foil and introducing ultrasonic vibration without rolling. This process resulted in the creation of samples shown in figure 4. Then the whole length of the foil was welded using the UAM process. The second sample was welded using the same set of UAM parameters as above, while the third sample was welded at a lower amplitude (12 μm). This method was followed to minimise the elongation of the foil on the direction of welding.

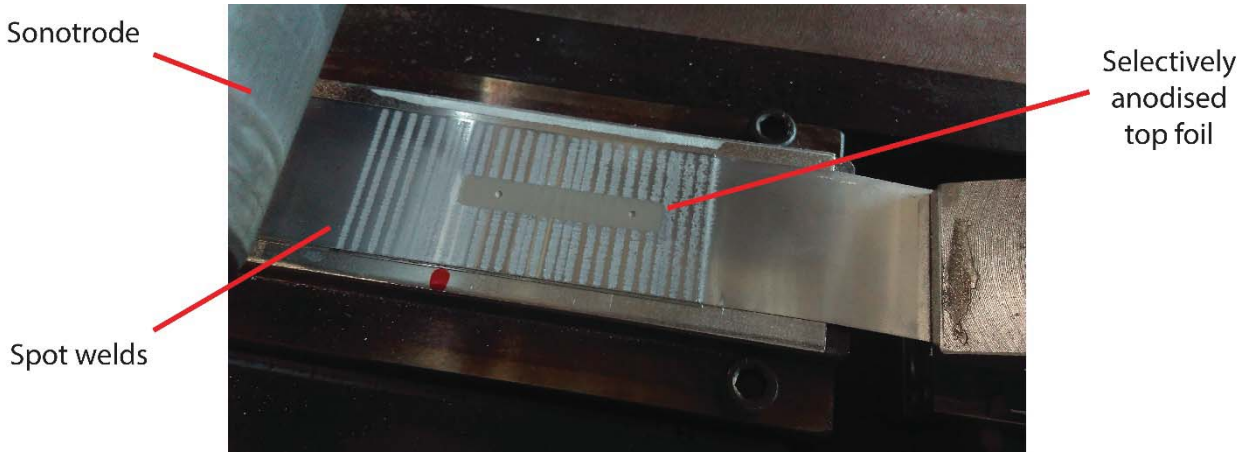


Figure 4: Sample with a series of ultrasonic spot welds

3.4 Conductive paste

For the creation of the conductive tracks a silver conductive polymer paste was manually deposited in channel of the second layer. The C2110817D5 paste (Gwent Electronic Materials Ltd.) was selected for this purpose, because of its excellent conductive properties (sheet resistivity approx. 30 Ω/square at 25μm thickness), its flexibility and its compatibility with the ceramic substrate. After deposition the ink was cured for 30 minutes at 150^{o}C in a box oven.

3.5 Evaluation

The surface morphology of the bonded foils was examined optically before and after bonding using an Alicona InfiniteFocus 3D surface measurement system. Step height and roughness measurements were taken using this system. All samples were electrically tested using a Keithley table-top multimeter before and after the bonding of the third layer. To further asses the performance of the anodic coating, all samples were cross sectioned at 3 locations width wise, polished and examined under an optical microscope (Eclipse MA200 inverted microscope, Nikon Metrology). The thickness of the AAO layer presented at figure 3 was measured by cross sectioning three samples per experimental point and examining them in the optical microscope.

4. Results & Discussion

Visual examination of the bonded selectively anodised samples that were initially spot welded revealed no signs of severe damage. On the other hand, cracks were visible on the surface of the sample that was prepared using the standard UAM process. The presence of cracks was especially prominent on the foil of the second layer: the machined channel acted as a stress concentrator and cracks initiated from its edges. This cracking was attributed to the elongation of the foil in the direction of welding during the UAM bonding, which can be significant (approx. 3% depending on the UAM process parameters [13]). The brittle AAO coating cannot withstand this elongation and thus mechanical failure occurs. This phenomenon can be overcome though, by creating a series of spot welds, similar to the method followed for the second and third samples, or by limiting the total length of the bonded area.

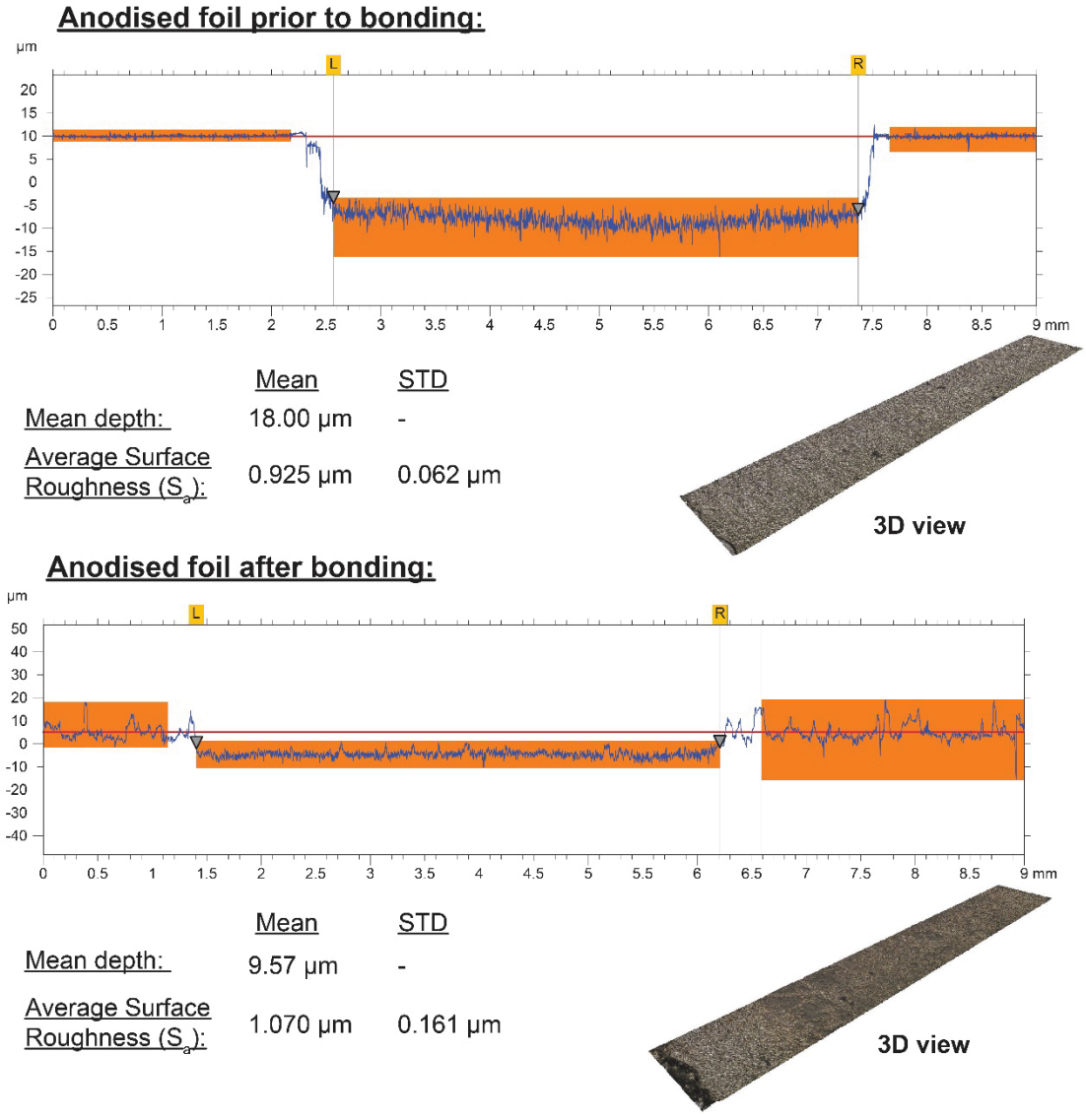


Figure 5: Representative line scan and 3D optical view of a selectively anodised aluminium foil (first layer - single sided) before and after UAM bonding.

The optical measurements also confirmed that only minimal damage was caused to the surface of the AAO coating during UAM bonding. In figure 5 measurement of the same foil before and after the ultrasonic welding are presented. It can be observed that the surface roughness (Ra) of the anodic coating before and after welding is almost unaltered. Also this observed surface roughness is compatible with all thick film electronic manufacturing materials [10]. For reference the average surface roughness (S_a) of the as-received foil was measured to be 0.120 μm, while the roughness of the foil after the electropolishing step was 0.450 μm.

In the same figure, the effect of the textured sonotrode on the exposed surface of the aluminium foil can also be seen: its surface roughness is significantly increased (S_a = 4.8 μm). Moreover the height difference between surface of the AAO coating and the surface of the aluminium foil is significantly decreased but not eliminated. This indicates that the sonotrode did not come in direct contact with the anodic coating and thus suggests that the material removed during the electropolishing step aided with protecting the integrity of the coating.

The electrical tests revealed short circuits between the conductive track and the aluminium matrix. In order to discover the source of this issue all samples were cross sectioned, polished and examined under an optical microscope. A typical cross section is presented in figure 6. Several shortcomings with the current methodology were identified. No bonding occurs in the ceramic-ceramic interfaces. This results in the creation of gaps between the insulating layers and can cause suboptimal bonding of subsequent layers, but also creates spaces where the conductive paste to flow prior to curing. The later can result in shorts between the conductive tracks and the metal matrix. Cracks in the anodic coating on the foil of the 1st layer were also identified. It is possible that these cracks originated from excessive loading during UAM bonding, but it is more likely to be the result of defects during the anodizing step, due to their morphology [16]. Nevertheless, no direct contact between the conductive track and the aluminium matrix through these cracks was observed. The most critical location for the creation of contact between the conductive track and the metal matrix is the area near the vertical walls. Previous works have reported inconsistencies in the growth of the AAO layer in non-flat surfaces [17]. This was also present on the sample prepared for this study and can be seen at the reduced thickness of the anodic coating at the edges between the vertical and horizontal walls. The reduced anodic layer thickness and the concentration of stress due to the morphology of these areas deem them critical for failure and for the creation of shorts between the conductive tracks and the metal matrix.

Despite the suboptimal outcome, the results of this study are promising for the encapsulation of conductive tracks and other electronic circuitry inside a metal matrix. In contrast to previous studies [4]–[6], excellent bonding quality between the metal-metal interfaces and no cracks in the boundary between the insulating layer and the metal matrix were observed. Moreover, the small dimensions of the embedded features introduces only minimal alteration to the properties of the base metal matrix and is expected to result in a minimal change of its mechanical properties. This initial study also highlighted the most important factors that cause the failure of the anodic layer and its results will drive forward future research.

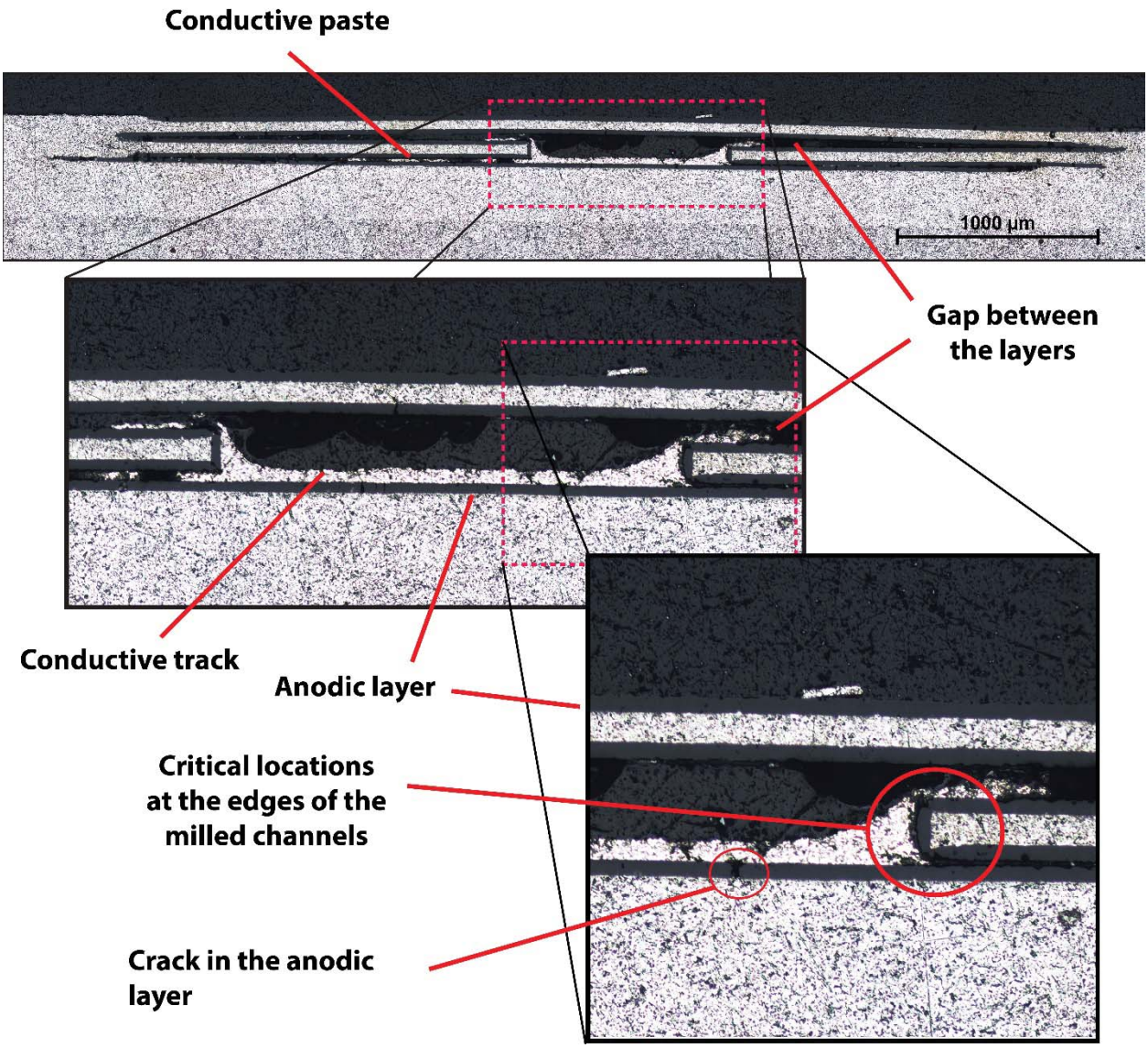


Figure 6: Cross section of a typical sample

5. Conclusions & Future work

In this paper, we outlined a new manufacturing methodology for the embedding of electronic circuitry, components and conductive tracks in an aluminium metal matrix. Even though ideal results have not yet been achieved, the outcomes of this initial investigative research are promising: it is possible to ultrasonically weld selectively anodised foils onto an aluminium substrate using UAM without causing severe damage to the anodic layer. Nevertheless, some challenges arose that will be addressed in the future. These include the generation of cracks and defects on the anodic aluminium oxide layer during UAM bonding and during preparation, the non-bonding between the interfaces of the anodic layers and the consistency of the conductive paste used for the creation of the conductive tracks. Possible solutions include the coating of the anodic layer with an adhesive or polymeric material prior to UAM bonding, the optimization of the foil preparation process and the selection of a more appropriate conductive material with a higher viscosity. All these alternatives will be examined in future work.

Acknowledgements

This work was supported by the Engineering and Physical Science Research Council (EPSRC) as part of the Centre for Innovative Manufacturing in Additive Manufacturing. References

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