ULTRASONIC ADDITIVE MANUFACTURING RESEARCH AT LOUGHBOROUGH UNIVERSITY

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Abstract

Ultrasonic Additive Manufacturing (UAM) has been subject to research and investigation at Loughborough University since 2001. In recent years, three particular areas of significant focus have been:

- The influence of pre-process material texture on interlaminar bonding.
- Secure fibre positioning through laser machined channels.
- Freeform electrical circuitry integration.

This paper details the key findings and a number of conclusions from these work areas. The results of this work have led to the further research and developmental applications for the UAM technology.

Introduction

Ultrasonic Additive Manufacturing (UAM) is a solid state additive manufacturing process that sequentially bonds metal foils together using ultrasonic metal welding (USW), layer by layer, and then uses Computer Numerical Control (CNC) machining to remove material to create the desired geometry (see Figure 1). UAM is therefore a hybrid of additive and subtractive manufacturing.
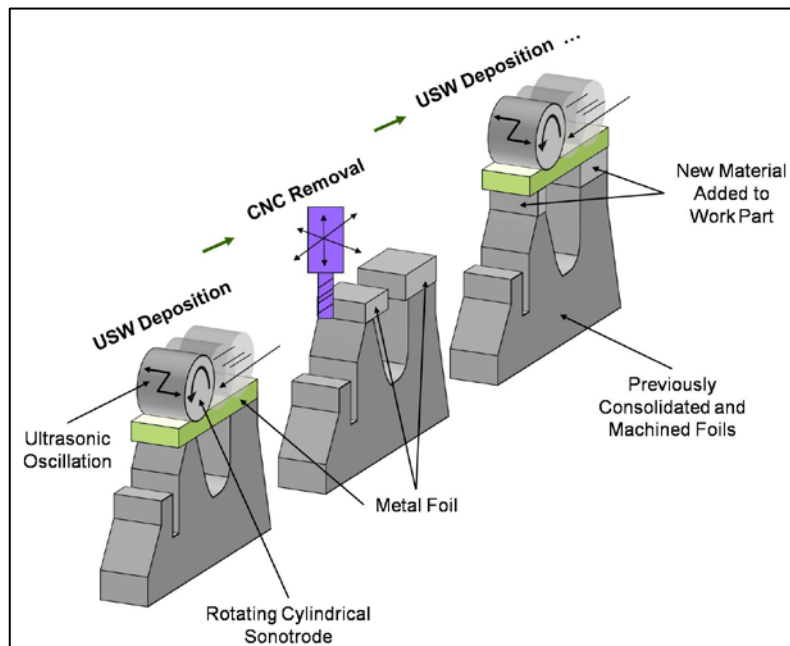

Figure 1 - Schematic of the UAM Process (1)

UAM has been researched at Loughborough University since 2001. Past research has involved:

Initial Characterisation

Using the Alpha UAM platform (Figure 2) work was carried out to identify the process parameter settings (i.e. weld speed (mm/s), weld pressure (KPa), and sonotrode oscillation amplitude (μm)) that resulted in the successful bonding of multi-layered aluminium alloy structures (2).
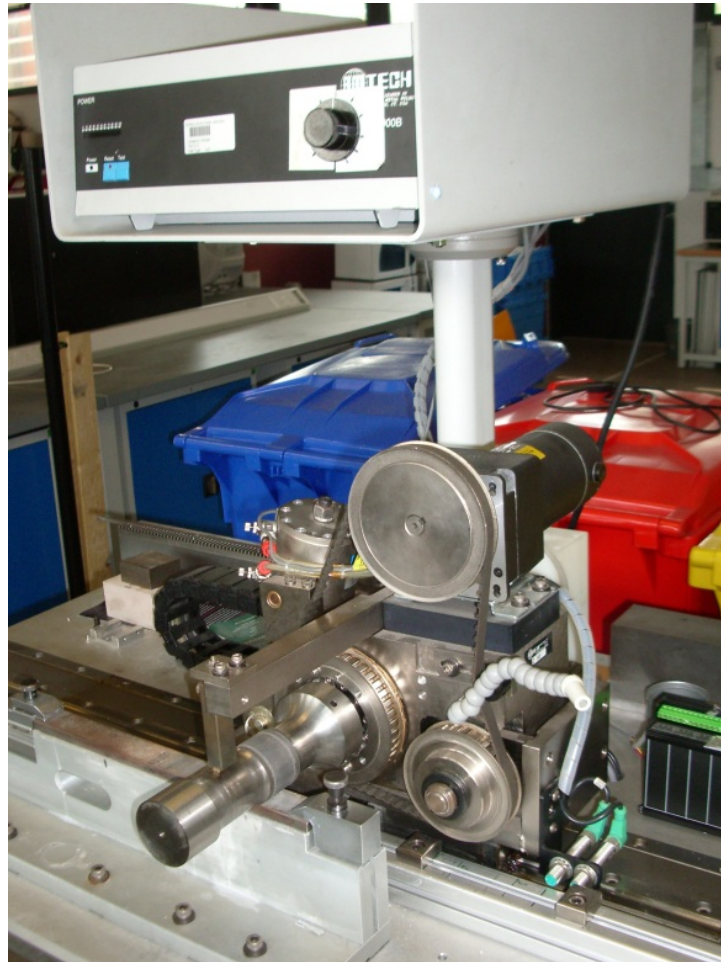
Figure 2 - The Alpha Ultrasonic Additive Manufacturing System

Interlaminar Bond Interface Quantification

A method of quantifying the bond between foil layers during the UAM process was devised and termed the Linear Weld Density (LWD) (3). This method of analysis involved cross-sectioning UAM samples, mounting, polishing and then microscopically analysing the samples to measure the level of porosity within the bond interface. This porosity was calculated via the LWD equation (*Lb* is the bonded length of the sample and *Lc* is the total bond interface length).

$$LWD\ (\%) = \left[\frac{Lb}{Lc}\right] \times 100$$

This quantification of the bond interface was also evaluated via the use of mechanical peel testing that was performed via the use of tensile testing equipment.

Object Embedding into Metal Matrices

By exploiting the 'acoustic softening' that occurs during ultrasonic processing of metal materials (4) it was found that objects could be embedded between the foil layers during the UAM process (5). This work led to the embedding of active elements such as Shape Memory Alloys (SMA) for actuation and optical fibres for data transfer as well as passive elements, such as Silicon Carbide (SiC) fibres for structural reinforcement (6) (7).
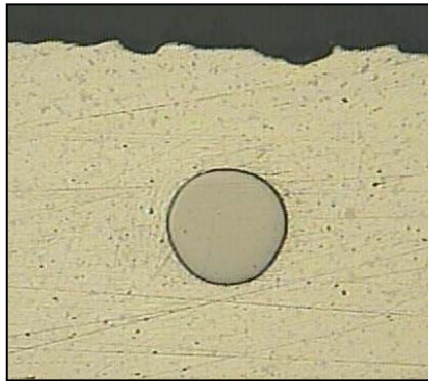
Figure 3 - Example of an Embedded Shape Memory Alloy Fibre in an Aluminium Alloy Matrix (8)

By embedding these objects it was demonstrated that due to the matrix compliance and relatively low processing temperature (typically <50% of the metal melt temperature (9) (10)) the UAM process was suited to the manufacture of metal matrix composites in the solid state.

Sonotrode Texture Importance

The sonotrode of the UAM equipment has an Electro Discharge Machined (EDM) surface that is used to ensure coupling between the metal foil surface and the tool (sonotrode) during the material processing. The importance of this texture was demonstrated via the use a smoother sonotrode surface that had occurred due to wear. It was found that this wear resulted in a reduced bond interface strength (evaluated via peel testing) and a reduced LWD (11).

Plastic Flow and Work Hardening during UAM

Investigation into the flow of the matrix material around embedded SiC fibres and the hardening of the matrix material (Figure 4) was performed using polarised light optical microscopy and micro-indentation equipment. This work highlighted the grain structure deformation caused by the fibre embedding and the resultant work hardening that was caused by the embedding process (12).
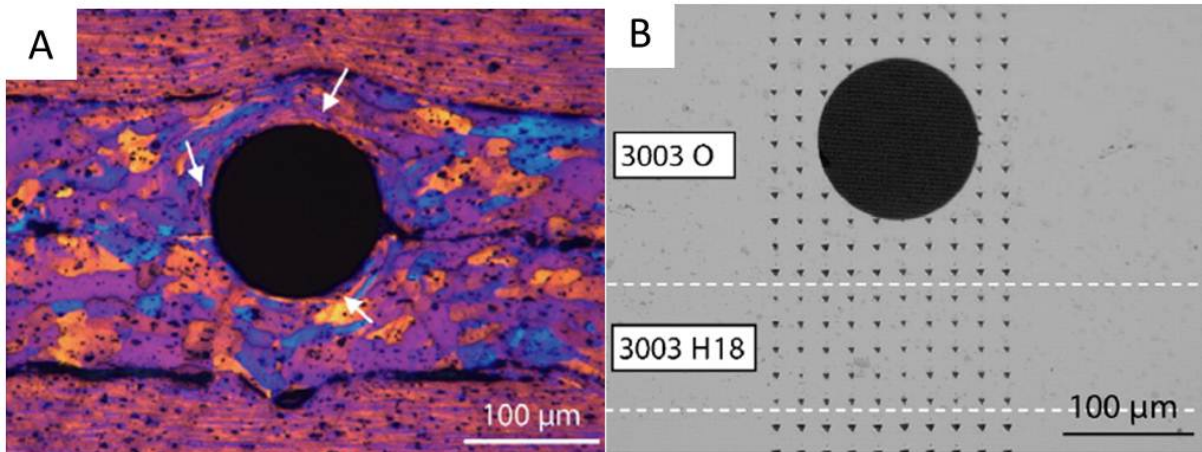
Figure 4 - Microscopy Highlighting Matrix Plastic Flow (A) and Microhardness Testing of Matrix Post-UAM (B) (12)

Interlaminar Sub-Grain Refinement

Using Dual Beam Focussed Ion Beam (DBFIB) analysis of the foil to foil interface, post UAM (Figure 5), it was identified that the sonotrode was causing sub-grain refinement in a highly localised area at the foil to foil interface and that this mechanism was resulting in a complex residual microstructure within the matrix (13) (14).
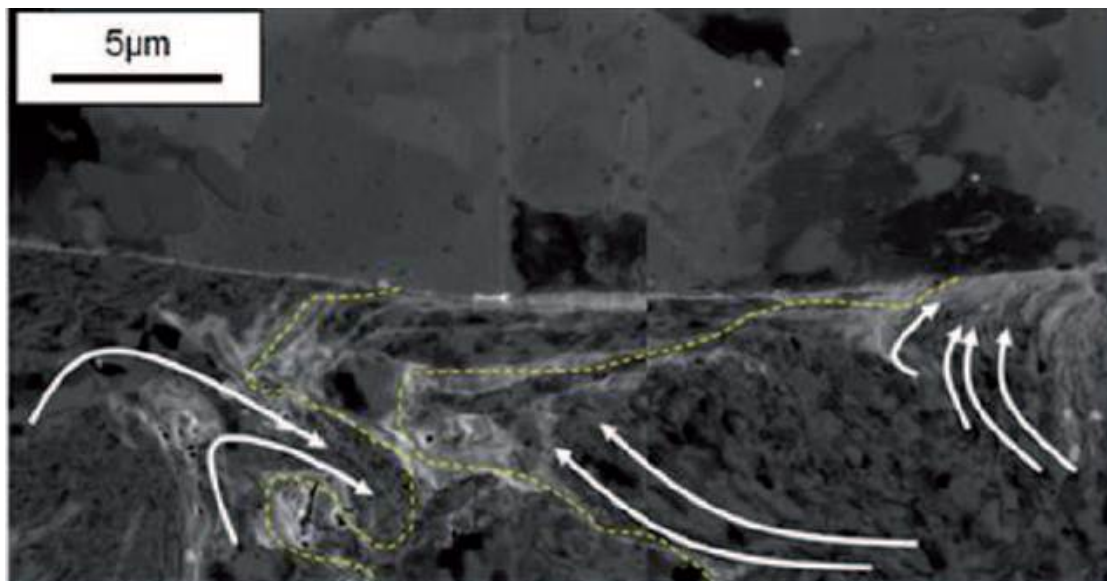

Figure 5 - DBFIB Image of Sub-Grain Refinement and Plastic Flow at the Bond Interface in a UAM Component (13)

Imparted Topology

Further work into the effects of the sonotrode texture identified that it was not only the sonotrode texture that was important for the UAM process. Using white light interferometry, peel testing, optical microscopy and LWD measurements researchers at Loughborough were able to identify that a key factor for the UAM process was the change in Interlaminar foil surface topology that was induced by the sonotrode contact (Figure 6). This topology change was found to be dependent on the sonotrode surface texture as well as the process parameters that were used during the UAM process (15).
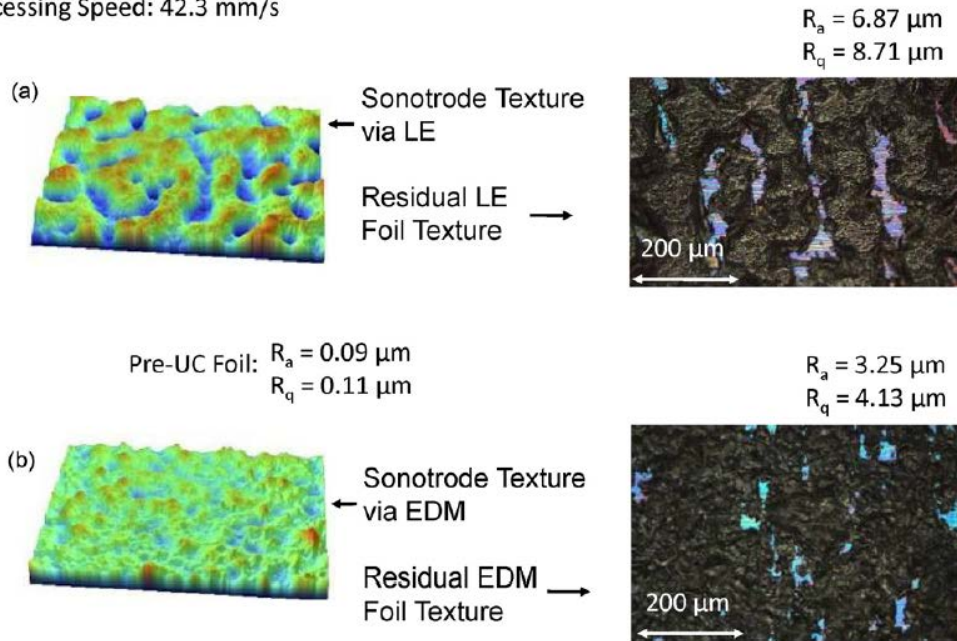
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Figure 6 - White Light Interferometry and Optical Microscopy Showing the Foil Topology Change Caused by Two Different Sonotorde Textures (a = rougher, b = smoother)

Sub-Grain Refinement due to Fibre Embedding

Through DBFIB analysis of the matrix around UAM embedded fibres it was uniquely identified that the embedding of objects into metal matrices via the UAM process results in sub-grain refinement that is similar to that induced by the sonotrode to foil contact (Figure 7) (16).
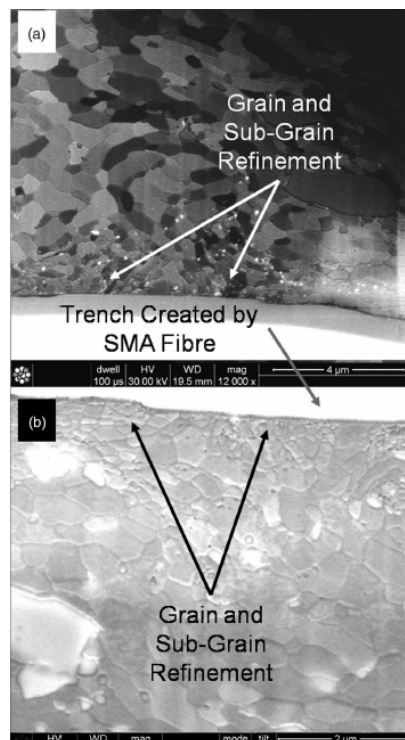

Figure 7 - Images Showing the Sub-Grain Refinement of the Matrix around UAM Embedded Fibres (a = DBFIB above the fibre, b = SEM above the fibre) (16)

Current UAM Work at Loughborough University

Current work at Loughborough University into UAM has been involved in key research focuses to maximise the potential of UAM. These are the detailed analysis of surface topography in UAM and the effects on interlaminar bonding (Figure 8) and the use of a fiber laser to create channels onto a UC sample surface for secure fibre placement and maximised matrix plastic flow (Figure 9).
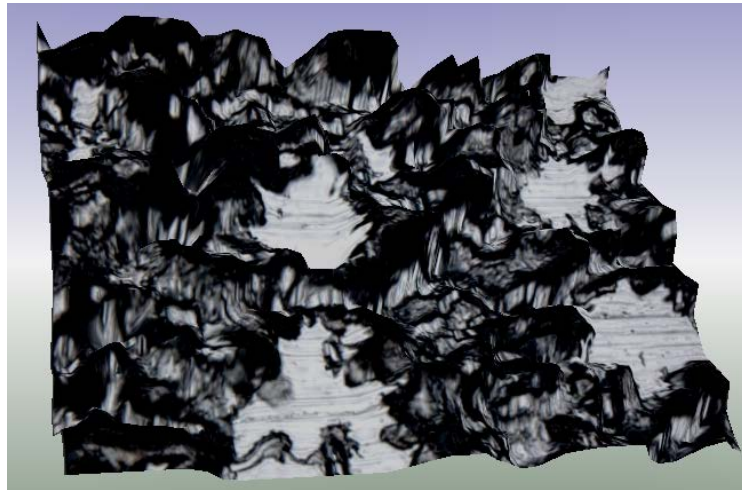

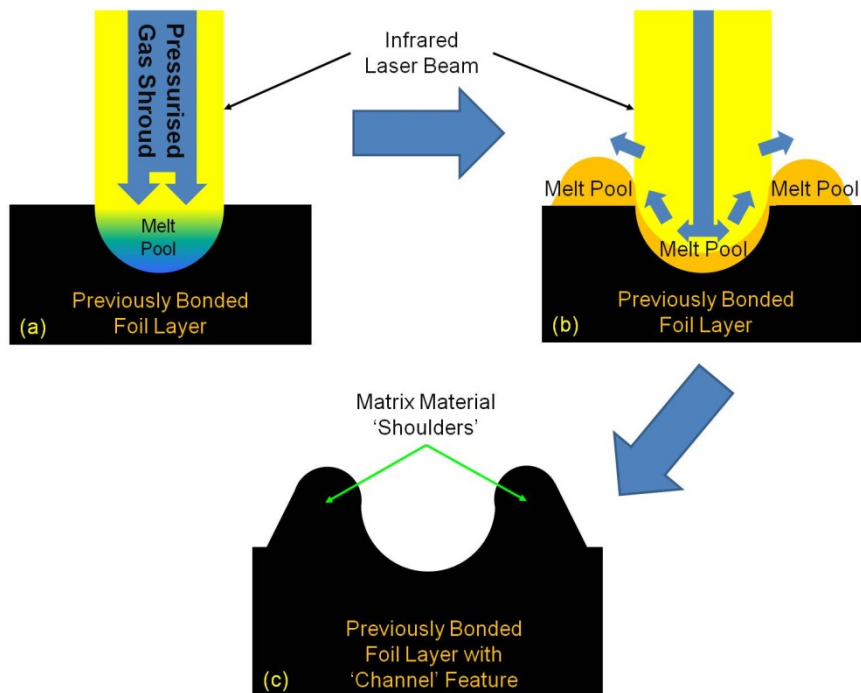**Figure 8 - Microscopic Detailed Analysis of the Interlaminar UAM Surface (15)**

Figure 9 - Schematic of the use of a Fiber Laser for Secure Fibre Postioning and Reduced PLastic Flow Requirements in UAM

Interlaminar Bonding in UAM

By using sonotrodes of varying surface textures and by using a full range of UAM processing parameters a detailed ANOVA study was performed. The process parameters

were related to the surface texture and the effect that this had on the resultant peel strength and LWD of the UAM samples. The surfaces of the sonotrode and samples were measured for a range of surface parameters using white light interferometry.

This detailed analysis led to new insight into the importance and effect of the sonotrode and thus foil surface topology for the UAM process. The key findings were:

- The most important factors for bond strength are the S_a of the sonotrode, the sonotrode amplitude and the weld pressure (S_a is > amplitude > weld pressure)
- Between the ranges measured in the study the weld speed was not found to be significant for UAM
- The sonotrode weld surface texture features of amplitude (Sa), spacing (Sal) and shape (Sku) emerged as the most influential factors that appear to effect interlaminar porosity and bond strength in UC.

Laser Channelling in UAM

The use of a fiber laser for channelling was shown to be successful for the creation of secure placement channels and should features to aid fiber embedding in UAM (Figure 10).
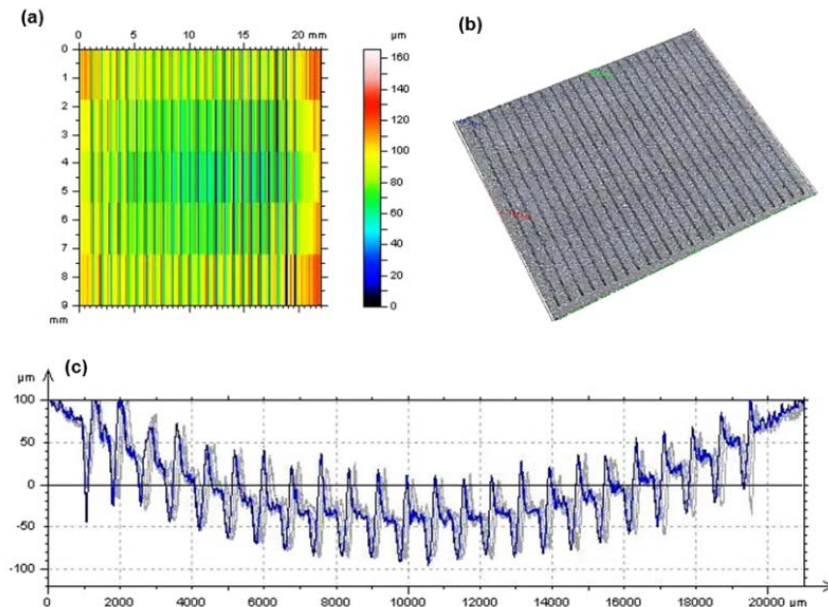
Figure 10 - White Light Interferometry Image Showing Multiple Channels on a UAM Sample Surface

Using optical microscopy, white light interferometry and EDAX the full effects of the laser processing on the UAM surfaces was characterised. The key findings of the work were:

- That using a multi-pass lasing technique allows for a smoother channel surface that more accurately follows a Gaussian profile.

- It is possible to create channels that are a diameter match to the intend fibres that will be embedded.

- That by using a carefully controlled gas flow rate during laser processing shoulder features can be created which would reduce the need for plastic flow around the fibres during UAM embedding. However this should feature is difficult to make symmetrical and usually has a bias to either side of the channel.

- Through the use of multiple laser passes a progressive Heat Affected Zone (HAZ) is created that results in an elemental compositional change in the UAM material.

Future UAM Work at Loughborough University

Future work into UAM at Loughborough University has begun to focus on improving and increasing the functionality of UAM parts through the integration of functional electrical circuitry during the UAM process (Figure 11). This work is being carried out in conjunction with a UK based SME with expertise in the printing of electronics – Printed Electronics Ltd.
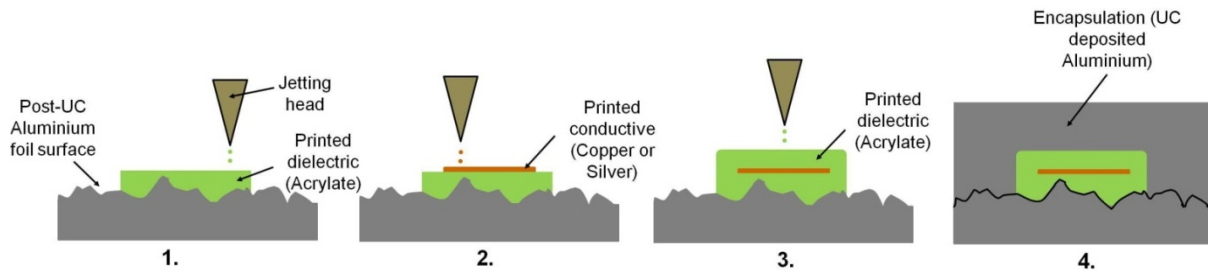

Figure 11 - Schematic of the Integration of Functional Electrical Circuitry into UAM Components via Inkjet Printing

By printing the electrical components and the insulating materials directly onto the UAM samples it has been possible to embed these electronics via the UAM process (Figure 12).
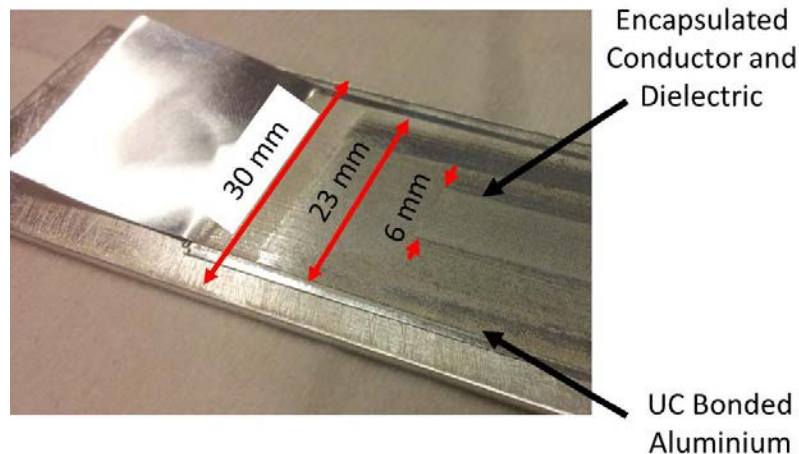

Figure 12 - UAM Sample with Embedded Functional Printed Electrical Circuitry

Further work will investigate the optimisation of the embedding process via the use of mechanical and microscopic analysis. The use of the components for further electrical testing will also be performed. The second major stage of the project will involve investigating the integration of the electrical circuitry in a 3D manner (i.e. in the z axis, perpendicular to the layup process).

Summary

Since 2001 multiple research projects into UAM have been performed by Loughborough University. This research has led to many important findings and essential work to helping maximise the potential of the UAM process.

The key areas of research have been:

- Process fundamentals for ensuring quality of bonding is maximised and that this is monitored through suitable techniques such as peel testing and LWD.

- Fibre embedding of multiple different types.

- Fibre-Matrix investigations into the micro and nano structural effects of the ultrasonic processing on interlaminar bonding and object embedding during UAM using analysis techniques such as SEM and DBFIB.

- Topology effects both in terms of the sonotrode and process parameters have been studied via the use of white light interferometry and ANOVA studies.

- Improving the application and functionality of UAM has and is continuing to be researched through the integration of functional, printed, electrical circuitry.

Research into UAM at Loughborough University is continuing and expansion for the future is now happening.

Acknowledgments

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