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Ultrasonic additive manufacturing – A hybrid production process for novel functional products

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Abstract

Ultrasonic Additive Manufacturing (UAM), or Ultrasonic Consolidation as it is also referred, is a hybrid form of manufacture, primarily for metal components. The unique nature of the process permits extremely novel functionality to be realised such as multi-material structures with embedded componentry. UAM has been subject to research and investigation at Loughborough University since 2001. This paper introduces UAM then details a number of key findings in a number of areas that have been of particular focus at Loughborough in recent years. These include; the influence of pre-process material texture on interlaminar bonding, secure fibre positioning through laser machined channels, and freeform electrical circuitry integration.

Selection and/or peer-review under responsibility of Professor Bert Lauwers

Keywords: Additive Manufacturing, Ultrasonic, Hybrid

1. 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 integrates Computer Numerical Control (CNC) machining to remove material to create the desired geometry during this additive build-up process (see Figure 1). UAM is therefore a hybrid of additive and subtractive manufacturing as the process incorporates, for example; layer manufacturing and welding, and machining and sometimes laser processing.

This combination of both additive build up by solid-state joining, with simultaneous selective subtractive processing provides a number of unique key manufacturing capabilities. In addition to the freeform geometry available from an additive/subtractive process UAM has the abilities to:

- Bond thermally and mechanically dissimilar materials to each other in the solid state (Figure 2).

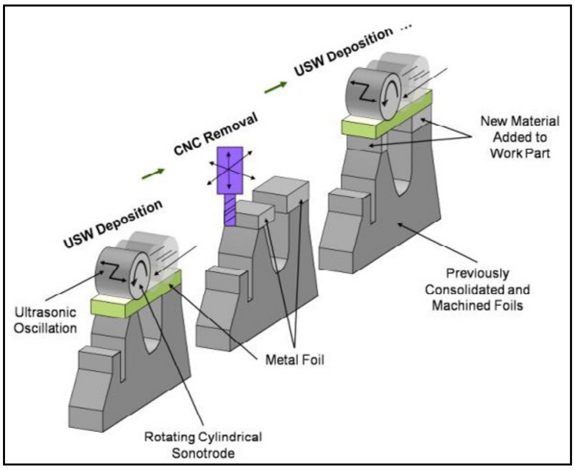

Figure 1 - Schematic of the UAM Process (1)

- Embed sensitive/functional components between the foil layers and bond the structure into a dense metal matrix (Figure 3).

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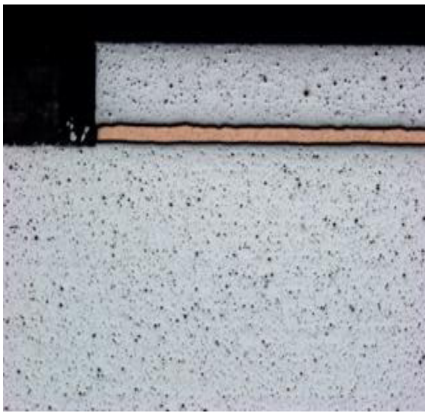

Figure 2 – Micrograph showing Al-Cu-Al laminate bonded via UAM (image courtesy of Fabrisonic LLC)

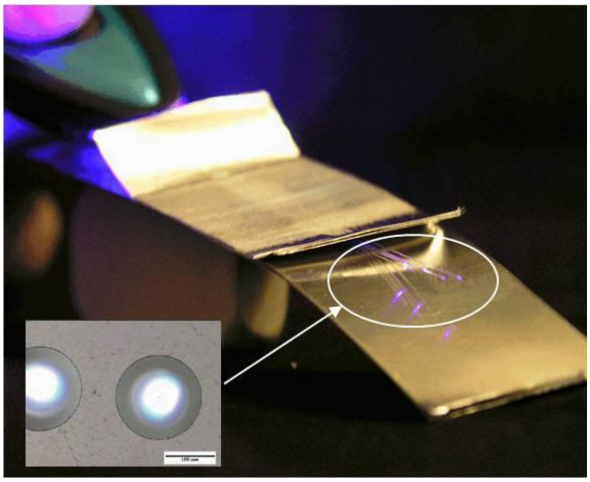

Figure 3 - Image showing UAM embedded single mode optical fibres within an Al matrix

There are a number of institutes active in UAM research, primarily situated in the USA, including University of Louisville, Clemson University, The Ohio State University, Oak Ridge National Laboratory, and Edison Welding Institute (EWI). UAM has been researched at Loughborough University since 2001 and a number of recent areas of work are the topic of this paper. This research has included the following areas of work which are overviewed with note to further detail in the accompanying references:

2. Processing window identification and Characterisation

Using the Alpha UAM (the World's first UAM equipment) platform (Figure 4) trailblazing experimental work was carried out to uniquely identify the key process parameter settings (i.e. weld speed (mm/s), weld pressure (KPa), and sonotrode oscillation amplitude (µm)) that resulted in the successful solid state bonding of multi-layered aluminium alloy structures (2).

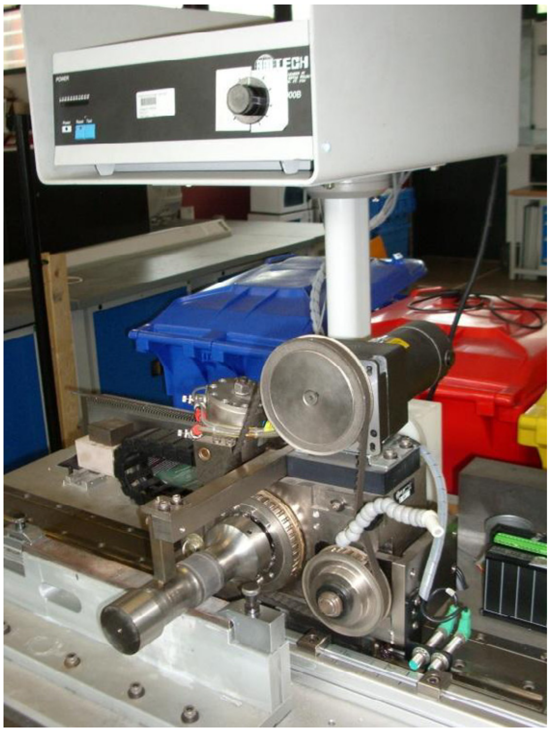

Figure 4 - The Alpha Ultrasonic Additive Manufacturing System

3. Interlaminar Bond Interface Quantification

Through the extensive experimental research work carried out by Loughborough a method was devised to quantifying the bond between foil layers during the UAM process, 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 any 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. These techniques were pertinent in providing analysis methods to drive forward the study of bond integrity and continue to be used by researchers in multiple institutions.

4. Object Embedding into Metal Matrices

By exploiting the 'acoustic softening' (a novel effect specific to ultrasonic bonding that causes low temperature high plastic flow) 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 signalling and condition monitoring, and passive elements such as Silicon Carbide (SiC) fibres for structural reinforcement (6) (7).

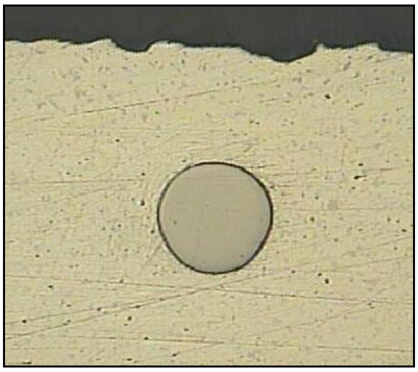

Figure 5 - Example of an Embedded Shape Memory Alloy Fibre in an Aluminium Alloy Matrix (8)

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 highly suited to the manufacture of high tech metal matrix composites with the valuable absence of high temperatures and/or pressures.

5. 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 initially identified through the use of 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) which has widespread implications for the industrial use of UAM and other ultrasonic bonding processes.

6. 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 6) 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 localised work hardening that was caused by the embedding process (12).

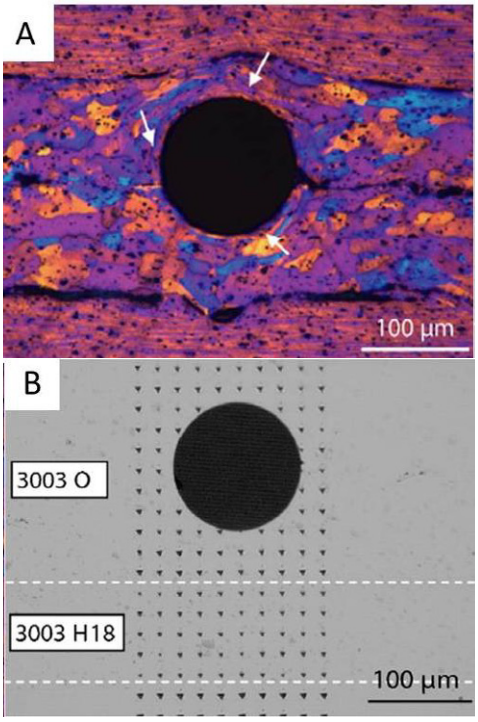

Figure 6 - Microscopy Highlighting Matrix Plastic Flow (A) and Microhardness Testing of Matrix Post-UAM (B) (12)

7. Interlaminar Sub-Grain Refinement

Using Dual Beam Focussed Ion Beam (DBFIB) analysis of the foil to foil interface, post UAM (Figure 7), 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). The nature of these grain structures is of particular interest to a wide number of industries and their study continues to be of significant focus.

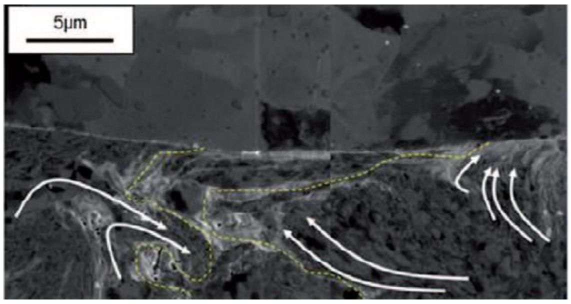

Figure 7 - DBFIB Image of Sub-Grain Refinement and Plastic Flow at the Bond Interface in a UAM Component (13)

8. Imparted Topology

Further work into the effects of the sonotrode texture identified that it was not only the sonotrode texture directly 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 8). This topology change was found to be dependent on the sonotrode surface texture but also the process parameters that were used during the UAM process (15).

9. 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 9) (16).

10. Current UAM Work at Loughborough University

Current work at Loughborough University into UAM has involved a number of key research focuses to maximise the potential of UAM. These include the detailed analysis of surface topography in UAM and the effects on interlaminar bonding (Figure 10), the use of a laser to create channels onto a UC sample surface for secure fibre placement and maximised matrix plastic flow (Figure 11), and the freeform printing of embedded electrical circuitry (Figures 13 and 14).

11. 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.

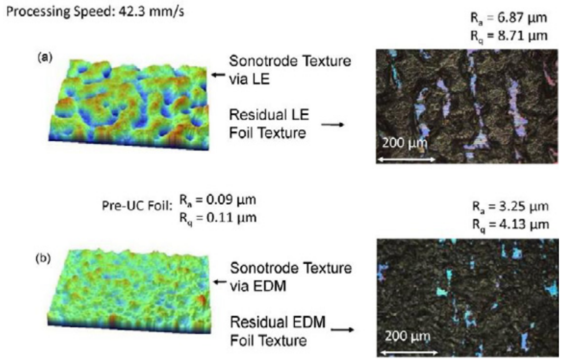

Figure 8 - White Light Interferometry and Optical Microscopy Showing the Foil Topology Change Caused by Two Different Sonotorde Textures (a = rougher, b = smoother)

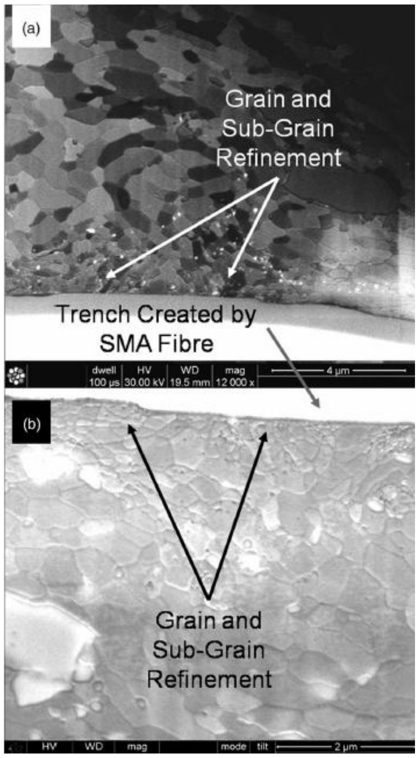

Figure 9 - Images Showing the Sub-Grain Refinement of the Matrix around UAM Embedded Fibres (a = DBFIB above the fibre, b = SEM above the fibre) (16)

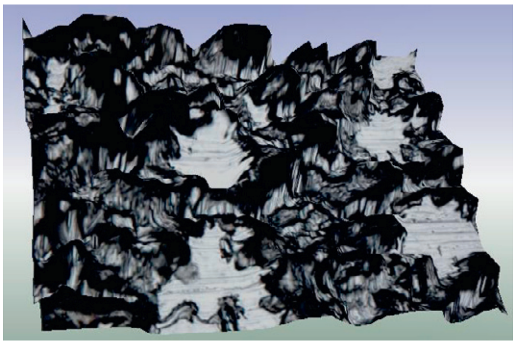

Figure 10 - Microscopic Detailed Analysis of the Interlaminar UAM Surface (15)

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 Sa of the sonotrode, the sonotrode amplitude and the weld pressure (Sa 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.

12. 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 accurate placement and positioning of fibre embedding in UAM (Figures 11 and 12).

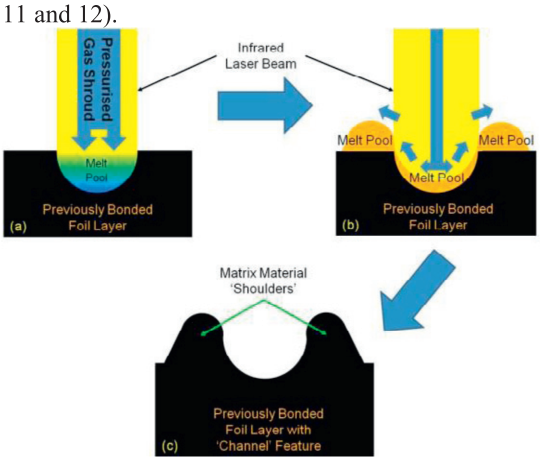

Figure 11 - Schematic of the use of a Laser for Secure Fibre Postioning and Reduced PLastic Flow Requirements in UAM

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.

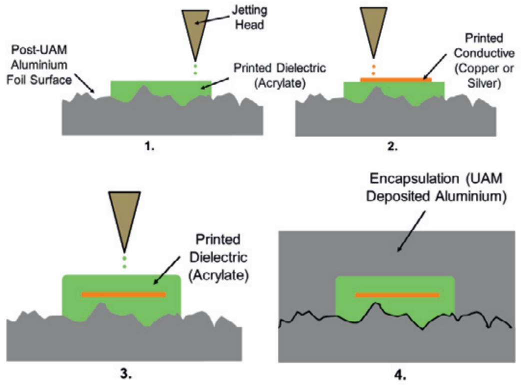

Figure 12 - Schematic of the Integration of Functional Electrical Circuitry into UAM Components via Inkjet Printing

- That it is possible to create channels that are a diameter matching to the intended 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 produce symmetrically and usually has a bias to Feither 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.

13. Freeform Printing of Embedded Electrical Circuitry

Further work into UAM at Loughborough University has begun to focus on further increasing the functionality of UAM parts through the freeform integration of functional electrical circuitry during the UAM process (Figure 12). This work is being carried out in conjunction with industrial partners.

By printing the electrically conductive components and the insulating materials as an appropriate construct directly onto the UAM samples it has been possible to embed these electronics, while retaining the functional construct, via the UAM process (Figure 13).

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

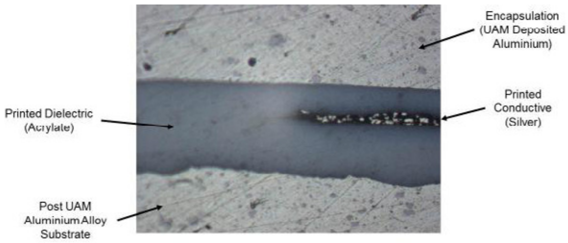

Figure 13 – Cross section of UAM Sample showing Embedded Functional Printed Electrical Circuitry

14. Summary

Since 2001 multiple research projects into UAM have been performed by Loughborough University. This research has led to many important findings and valuable 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 expanding.

Acknowledgements

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