Materials Science & Engineering A 639 (2015) 474–481

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Exploring the mechanical strength of additively manufactured metal structures with embedded electrical materials

J. Li*, T. Monaghan, S. Masurtschak, A. Bournias-Varotsis, R.J. Friel, R.A. Harris

Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK

ARTICLE INFO

Article history:
Received 11 January 2015
Received in revised form
22 March 2015
Accepted 10 May 2015
Available online 18 May 2015

Keywords:
Ultrasonic Additive Manufacturing
3D printing
Layered manufacturing
Aluminium
Embedded electrical materials
Mechanical strength

ABSTRACT

Ultrasonic Additive Manufacturing (UAM) enables the integration of a wide variety of components into solid metal matrices due to the process induced high degree of metal matrix plastic flow at low bulk temperatures. Exploitation of this phenomenon allows the fabrication of previously unobtainable novel engineered metal matrix components.

The feasibility of directly embedding electrical materials within UAM metal matrices was investigated in this work. Three different dielectric materials were embedded into UAM fabricated aluminium metal-matrices with, research derived, optimal processing parameters. The effect of the dielectric material hardness on the final metal matrix mechanical strength after UAM processing was investigated systematically via mechanical peel testing and microscopy. It was found that when the Knoop hardness of the dielectric film was increased from 12.1 HK/0.01 kg to 27.3 HK/0.01 kg, the mechanical peel testing and linear weld density of the bond interface were enhanced by 15% and 16%, respectively, at UAM parameters of 1600 N weld force, 25 μm sonotrode amplitude, and 20 mm/s welding speed. This work uniquely identified that the mechanical strength of dielectric containing UAM metal matrices improved with increasing dielectric material hardness. It was therefore concluded that any UAM metal matrix mechanical strength degradation due to dielectric embedding could be restricted by employing a dielectric material with a suitable hardness (larger than 20 HK/0.01 kg). This result is of great interest and a vital step for realising electronic containing multifunctional smart metal composites for future industrial applications.

1. Introduction

Ultrasonic Additive Manufacturing (UAM) utilises Ultrasonic Metal Welding (UMW) to weld metal foils layer by layer, and then periodically applies Computer Numerical Control (CNC) machining to produce a 3D metal structure [1] (Fig. 1). During the UAM process, energy generated from an ultrasonic transducer is transferred to a work piece through a textured sonotrode in the form of ultrasonic oscillations. With a compressive normal force via the sonotrode, the oscillations cause friction/scrubbing at the mating surfaces; this disrupts oxide films at the interface and generates clean metal to metal contact points. Plastic deformation of nascent metal beneath the contact surfaces further helps the break-up of the oxide layer and the generation of further new clean contact points. The result of the compression and ultrasonic oscillation is a solid state weld resulting in true metallurgical bonding at the contact interface [2].

Due to two key abilities, UAM enables the integration of a wide variety of components into solid metal matrices. Firstly, UAM is a solid state bonding process and the bulk temperature increase during processing is normally lower than 50% of the melting point of the metals to be consolidated, which would avoid potential damage to thermally sensitive embedded components caused by thermal stress and melting [3]. Secondly, large plastic flow of the metal matrix during ultrasonic excitation permits the full encapsulation of inserted components [4]. In addition to the two key abilities of UAM the process is also faster than many other metal AM processes, so it is capable of building large metal components in a comparatively short period of time. Lastly, the UAM process can be paused in an ambient temperature and atmosphere and left for essentially any amount of time and then restarted again without adverse effects. This makes an ideal system for integrating electrical components into solid metal matrices in a layer-by-layer fashion.

With the UAM process, Kong et al. [5] and Mou et al. [6] successfully embedded optical fibre sensors into aluminium matrices. Furthermore, pre-packaged electronic systems and direct-written circuitries have also been encapsulated in UAM metal structures

* Corresponding author. Tel.: +44 1509227567.
E-mail address: J.Li5@lboro.ac.uk (J. Li).

http://dx.doi.org/10.1016/j.msea.2015.05.019
0921-5093/

by Siggard et al. [7] and Robinson et al. [8], respectively. However, UAM embedded electronics at current state-of-art still have some limitations: (1) the electronic encasing and circuiting are still in 2D planar and no 3D freeform embedding capability has been demonstrated which restricted the range of applications and the freedom of design and manufacture; (2) the integration level of the metal structure was relatively low due to the large size of the embedded electronic components; (3) extra process steps such as milling protection pockets and channels for electronic components and padding them with epoxy were required which confounded the manufacturing process; (4) the large volume pockets and channels milled for electronics placement degraded the mechanical strength of the structure as a whole. Although this previous research has shown that electronics and sensor integration with UAM is possible it is pertinent to now explore an entirely new realm of multifunctional structures via the direct (i.e. with no extra process step such as pocket machining) integration of printed electronic techniques with UAM to possibly attain never before achieved multi-functional metal matrix composites.

To attain these multi-functional metal matrix composites the compatibility and effects of electronic materials with UAM must first be established. This paper documents the findings of that investigation of UAM embedded dielectric materials.

2. Experimental methodology

2.1. Materials

A 5 mm thick and 30 mm wide aluminium (Al) 1050 H14 plate was used as a base plate for the UAM process, and two Al 3003 H18 foils with a thickness and width of 100 μm and 24 mm respectively were ultrasonically welded onto the Al 1050 base plate to create the UAM metal matrices. The mechanical properties and chemical composition of Al 1050 and Al 3003 are summarised in Table 1 [9,10].

To identify the compatibility between UAM process and dielectric materials, a significant preliminary embedding experimentation was performed with a wide range of candidate dielectrics. It was found that the range of materials capable of actually being embedded via UAM was limited. Three identified dielectric inks, LuxPrint® 8153 from DuPont™, 520 Series Soldermask made by Technic, and Imagecure® AQ XV501T-4 of Sunchemical® were finally employed in this work. These inks are all commercial products that are widely used in the printed electronics industry. 8153 is a single part thermal curable ink for manufacturing screen-printed Electroluminescent (EL) lamps, while both 520 Series and XV501T-4 are two-component solder resists used in rigid printed circuit boards (PCBs). In tests, all three inks were solidified thermally as per the manufacturer's instructions and the parameters used are shown in Table 2 [11–13].

2.2. UAM apparatus

The UAM apparatus used in this research was the Alpha 2 UAM machine supplied by Solidica INC. (USA) as shown in Fig. 2. The Alpha UAM machine works with an input power of 20 kW and a constant frequency of ~20 kHz. Three control parameters of the apparatus, normal force (N), sonotrode amplitude (μm), and welding speed (mm/s), can be varied by users to adjust the energy applied to the workpieces. The normal force is the downward force of the sonotrode on the metal foil to be welded that permits close contact between metal foil and substrate, and can be varied from 100 N to 2000 N. The sonotrode amplitude refers to the longitudinal oscillatory displacement of the sonotrode that can be varied within a range

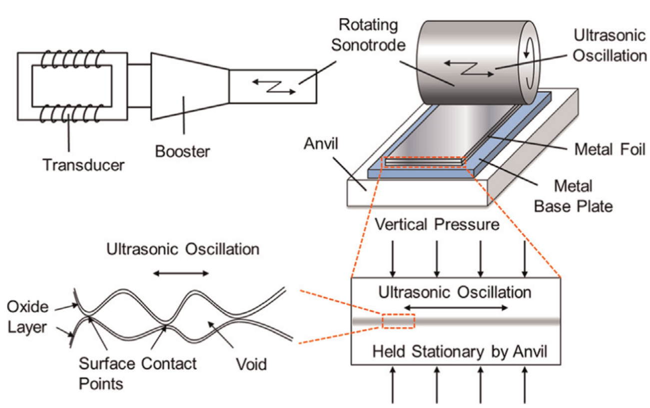

Fig. 1. Schematic drawing of Ultrasonic Additive Manufacturing (UAM).

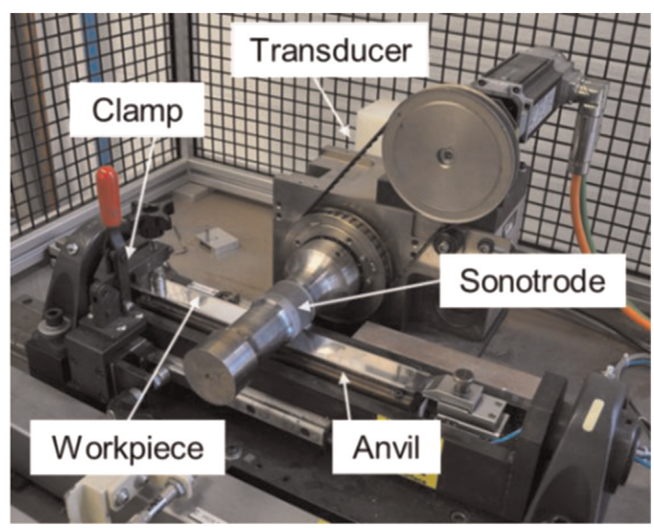

Fig. 2. Alpha 2 UAM Machine.

Table 1
Mechanical properties and chemical composition of Al 1050 H14 and Al 3003 H18.

	Al 1050 H14	Al 3003 H18
Density (g/cm^3)	2.71	2.73
UTS (MPa)	100–135	200
Tensile yield strength (MPa)	75	186
Elongation at break (%)	4–8	1–4
Modulus of elasticity (GPa)	69	68.9
Melting temperature (°C)	645–657	643–654
Composition (wt%)	Al (≥ 99.08), Mn (≤ 0.05), Cu (≤ 0.05), Fe (≤ 0.4), Si (≤ 0.25), Zn (≤ 0.07), Mg (≤ 0.05), Ti (≤ 0.05), Other (≤ 0.03)	Al (96.7–99), Mn (1–1.5), Cu (0.05–0.2), Fe (≤ 0.7), Si (≤ 0.6), Zn (≤ 0.1), Other (≤ 0.15)