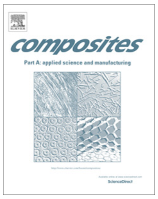
Composites: Part A 76 (2015) 181–193

Contents lists available at ScienceDirect

Composites: Part A

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



Solid-state additive manufacturing for metallized optical fiber integration

T. Monaghan [*], A.J. Capel, S.D. Christie, R.A. Harris, R.J. Friel

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

ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form 27 April 2015
Accepted 3 May 2015
Available online 6 June 2015

Keywords:
A. Metal-matrix composites (MMCs)
A. Layered structures
A. Fibers
Ultrasonic Additive Manufacturing (UAM)

ABSTRACT

The formation of smart, Metal Matrix Composite (MMC) structures through the use of solid-state Ultrasonic Additive Manufacturing (UAM) is currently hindered by the fragility of uncoated optical fibers under the required processing conditions. In this work, optical fibers equipped with metallic coatings were fully integrated into solid Aluminum matrices using processing parameter levels not previously possible. The mechanical performance of the resulting manufactured composite structure, as well as the functionality of the integrated fibers, was tested. Optical microscopy, Scanning Electron Microscopy (SEM) and Focused Ion Beam (FIB) analysis were used to characterize the interlaminar and fiber/matrix interfaces whilst mechanical peel testing was used to quantify bond strength. Via the integration of metallized optical fibers it was possible to increase the bond density by 20–22%, increase the composite mechanical strength by 12–29% and create a solid state bond between the metal matrix and fiber coating; whilst maintaining full fiber functionality.

1. Introduction

Ultrasonic Additive Manufacturing (UAM) is a solid state metal Additive Manufacturing (AM) process that utilizes ultrasonic oscillations to bond metal tapes layer by layer before using periodic Computer Numerical Controlled (CNC) machining to fabricate complex three-dimensional components [1].

In UAM a rolling cylindrical horn, also known as a sonotrode, applies the ultrasonic oscillations generated by an ultrasonic transducer to the thin metal tapes (ca. thickness 50–200 μm). Due to sonotrode dynamics, ultrasonic oscillations and compressive normal forces applied through the sonotrode, interfacial stresses and intimate contact between mating foil surfaces are induced. This leads to disruption of typically stubborn oxide layers and induces both static and shear forces within the metallic foils. The result of which is elastic–plastic deformation of surface asperities, newly formed nascent surfaces and true metallurgical bonding between the foil and substrate [2–4]. A schematic of typical UAM processing equipment is detailed in Fig. 1. The strength and quality of the final part produced is directly related to several processing parameters controlled by the operator, including; normal force applied by the sonotrode (ca. 500–2000 N), traverse speed of sonotrode (ca. 10–100 mm/s), amplitude of sonotrode oscillation (ca. 10–50 μm), build platform temperature (ca. 25–200 °C) and the surface topography of the sonotrode [5,6].

The use of UAM in the formation of Metal Matrix Composites (MMC's) has been the subject of multiple studies [7,8]. The unique nature of the bonding mechanism within UAM makes it ideally suited to the manufacture of MMC's featuring both smart and passive integrated components. Firstly, the low temperatures associated with UAM allows for the incorporation of thermally sensitive components within solid metal structures. Metallurgical bonding at the weld interface can typically be achieved at temperatures approximately 30–50% of the matrix absolute melting temperature [5]. This reduction in processing temperature avoids thermal stresses arising from mismatches in the coefficients of thermal expansions as well as melt points – a common feature in other metal additive manufacturing processes [9,10]. Furthermore, as the deposited material is not elevated above its melt temperature, as is the case in powder bed fusion techniques such as Selective Laser Melting (SLM) and Selective Laser Sintering (SLS), issues such as embrittlement, residual stress and distortion of parts are significantly reduced. A second unique feature of UAM that makes it highly suitable for manufacturing MMCs is the large degree of localized plastic flow observed in the interlaminar region during foil deposition. This plastic flow allows for sound mechanical encapsulation of components by the matrix material [11]. To date, this ability has been utilized to incorporate a variety of fibers such as Silicon Carbide (SiC) for localized stiffening, Shape Memory Alloy (SMA)

---

[*] Corresponding author. Tel.: +44 01509 227586.
E-mail address: T.monaghan@lboro.ac.uk (T. Monaghan).

http://dx.doi.org/10.1016/j.compositesa.2015.05.032
1359-835X/© 2015 The Authors. Published by Elsevier Ltd.

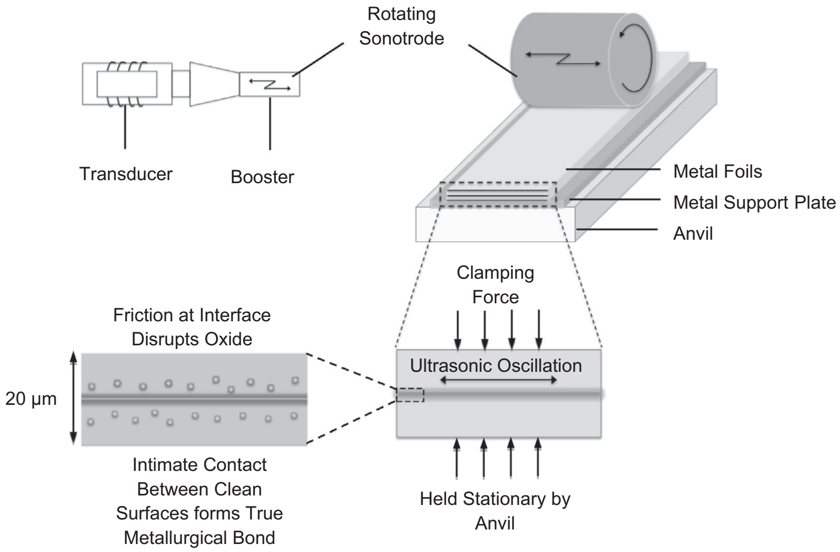


Fig. 1. Schematic diagram of a typical UAM set-up detailing the interfacial welding zone.

for actuation and optical fibers for sensing [12–14]. Other pre-fabricated components such as pre-packaged electronic systems and direct-written circuitries have been successfully incorporated into UAM structures [15,16]. For these reasons, UAM remains an appealing alternative to other higher temperature manufacturing techniques for manufacturing smart MMC structures.

The ability to successfully incorporate optical fibers within a metal matrix has the potential for application in areas such as structural fatigue/damage monitoring as well as real-time temperature, pressure and strain monitoring, in otherwise inaccessible locations [17,18]. Employing directly integrated fiber-optic sensors allows not only for potential reductions in component size and weight, they also benefit from increased corrosion resistant, greater immunity to electromagnetic interference and improved sensitivity. It is these qualities that often permit the use of fiber-optic strain sensors in a large variety of applications and harsh environments less suited to conventional resistive foil strain gauges. Their small size and geometric compatibility with composite materials allows them to be relatively non-perturbative when embedded, allowing for in situ strain monitoring within composite laminate structures and has led to their increased use in smart structure applications [17]. Previous work by Mou and co-workers demonstrated through thermal and loading responses of MMC's with embedded optical fibers containing laser etched FBGs embedded that they demonstrated self-sensing capabilities [18]. It was noted however that dissimilarities in the thermal expansion coefficient of the embedded FBG and surrounding matrix can lead to issues with FBG peak shifting as a result of similar expansion rates of the materials when subjected to heat. It was hypothesized that a different thermal sensitivity enhancement could be obtained if Aluminum were replaced with a different metal alloy with a substantially different thermal expansion coefficient. Yet, the work from Kong et al. still represents the most significant of its kind. A substantial contributor to the lack of following publications in this area is due to the frail nature of the UAM/optical fiber composite structures, post processing. In order for Kong to successfully encapsulate the silica optical fibers within the metal matrix, it was necessary to first remove the protective acrylic polymer coating surrounding the fiber [14]. Therefore, after successful encapsulation, the fibers often fracture at the weld interface when handled. Increasing the robustness of the fiber through the application of metallic coatings could potentially allow for the utilization of optimal UAM processing conditions. This in turn could lead to superior mechanical properties of the MMC structures produced.

Li and co-workers recently reported the application of Nickel coatings to optical fibers as a means of improving the durability of Fiber Bragg Gratings (FBG's) encapsulated through Ultrasonic Spot Welding (USW) [19]. Ultrasonic Spot Welding (USW) is a welding technique capable of joining non-ferrous similar and dissimilar metal components, at small localized points, through the use of high frequency sound energy to soften or melt the material under an applied pressure. Their results showed that through chemical-electroplating, a degree of protection can be afforded to the fibers from the spot-welding process with little or no effect of the wavelengths transmitted or the sensing capabilities of the fiber. These results are a good indication of the potential benefits of applying protective metal coatings to fibers prior to ultrasonic encapsulation, however spot welding itself is only capable of achieving small regions of consolidation in a static fashion – not large area bonding and continuous fiber integration that would be required for MMC manufacture.

As a result of this past work it would be pertinent to investigate both the effects of this protective fiber coating technique under UAM processing conditions and gain insight into how the ultrasonic fiber/matrix integration process performs in a continuous embedding manner as opposed to a singular spot-weld. This combination of UAM and metal coated optical fibers potentially allows the creation of more robust optical fiber based smart MMCs. The ability to embed optical fibers at a wide range of parameters, whilst still maintaining their functionality, has the potential to increase the scope of applications for UAM in the formation of the smart MMC structures. This paper is an investigation into the effect of UAM processing on metallized optical fibers (both Aluminum and Copper coated), the strength of the composite structures they yield, and how the UAM process performs in a continuous embedding manner on these fibers.

2. Methodology

2.1. Materials

Aluminum (Al) 3003 H18 foils, at ∼100 μm thick and ∼24 mm wide, were chosen as the matrix material in which the selected fibers were to be embedded. This material is readily available in