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Interfacial shear strength estimates of NiTi–Al matrix composites fabricated via ultrasonic additive manufacturing

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ABSTRACT

The purpose of this study is to understand and improve the interfacial shear strength of metal matrix composites fabricated via ultrasonic additive manufacturing (UAM). NiTi–Al composites can exhibit dramatically lower thermal expansion compared to aluminum, yet blocking stresses developed during thermal cycling have been found to degrade and eventually cause interface failure in these composites. In this study, the strength of the interface was characterized with pullout tests. Since adhered aluminum was consistently observed on all pullout samples, the matrix yielded prior to the interface breaking. Measured pullout loads were utilized as an input to a finite element model for stress and shear lag analysis. The aluminum matrix experiences a calculated peak shear stress near 230 MPa, which is above its ultimate shear strength of 150–200 MPa thus corroborating the experimentally-observed matrix failure. The influence of various fiber surface treatments and consolidation characteristics on bond mechanisms was studied with scanning electron microscopy, energy dispersive X-ray spectroscopy, optical microscopy, and focused ion beam microscopy.

1. Problem statement and introduction

Ultrasonic additive manufacturing (UAM) is a recently developed rapid prototyping process where thin foils of similar or dissimilar metals are ultrasonically welded together in a layer by layer process to form gap-less, 3D metal parts [1]. Along with welding, periodic machining is utilized during the UAM process to implement complex designs, features, and to remove material for embedding various objects into the structure, such as reinforcing fibers. A schematic of the UAM process is shown in Fig. 1.

Due to the physics of ultrasonic welding, metallic bonding takes place at temperatures far below metallic melting temperatures. Thus, temperature sensitive materials such as nickel titanium (NiTi) shape memory alloys can be combined or built into metallic structures. Current UAM systems utilize 9 kW of ultrasonic power, nearly an order of magnitude higher than early UAM equipment. The increase in weld power allows for higher process down force and higher quality interfacial properties between foils and between foils and embedded fibers [2].

Recently, UAM has been utilized to fabricate aluminum matrix composites with embedded NiTi shape memory alloy fibers for thermally invariant components. Specifically, when the composite is heated, the strain recovery of the NiTi fibers counteracts the expansion of the aluminum matrix. This combination creates a low density, stiff, and thermally stable material for engineering applications. Previous efforts have shown a 60% reduction in the average coefficient of thermal expansion for Al 3003 up to 100 °C [3]. Yet, metallic bonding between the aluminum matrix and NiTi fibers is not always observed. Instead, the interface is believed to be predominately supported by mechanical coupling in the form of a friction fit [4]. Although it is desirable to achieve metallic bonding at the interface, mechanical coupling may be sufficient if the interface strength exceeds thermal blocking stresses generated throughout temperature cycling. However, previous efforts have shown evidence of interface failure when significant blocking stresses arise [4].

To further investigate the high temperature interface failure, interfacial shear stresses of NiTi–Al 6061 composites are estimated through single fiber pullout tests [5]. Understanding the strength and failure characteristics of the interface is critical for designing reliable and robust NiTi composites. Pullout testing has been found to be effective in estimating interface strength and understanding failure behavior in polymeric composites with embedded NiTi

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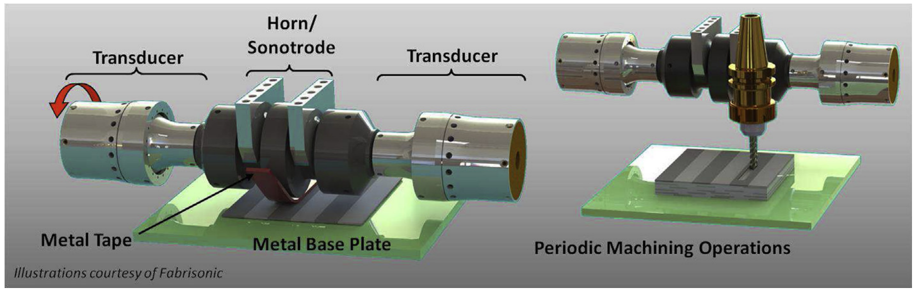

Fig. 1. Ultrasonic additive manufacturing process for developing novel and unique metal composites and designs.

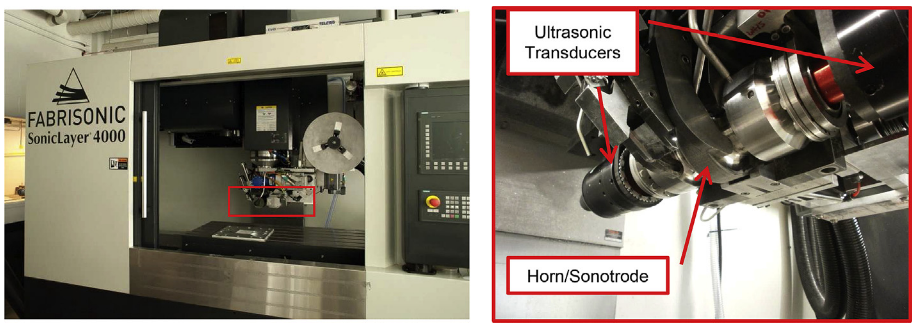

Fig. 2. Current 9 kW UAM system with sonotrode and ultrasonic welder assembly boxed in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

[6–13]. In addition to estimating strength, the influence of various surface treatments on the NiTi fibers was investigated for possible improvement of the interface strength and bonding behavior. The surface treatments investigated are as-built oxide (past surface finish of use and control), chemically etched, mechanically polished, and mechanically roughened. The chemically etched and mechanically polished finish increase the likelihood that metallic bonding may take place due to the as-built oxide layer being removed. On the other hand, the mechanically roughened surface would potentially increase the mechanical interlocking and increase the likelihood of metallic bonding. To complement the fiber pullout tests, scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) were utilized to compare and contrast bond type and quality for each NiTi surface finish. Additionally, optical microscopy and focused ion beam (FIB) microscopy were utilized to analyze interface failure behavior and matrix microstructure around embedded fibers.

2. Methods

2.1. Sample manufacture

In this study, Al 6061-H18[1] was utilized as the metal matrix for the NiTi–Al UAM composites. Al 6061 was chosen due to its frequent use in industry and strong compatibility with UAM. Samples were manufactured on a 9 kW UAM system [14], Fig. 2. The machine has a fully automated tape feed, a computer numerical control (CNC) stage, and a laser machining stage to complement the ultrasonic welder.

The NiTi fiber diameter utilized in this study, for all surface finish types, was 0.28 mm (0.011″), as supplied by Nitinol Devices and Components, Inc. The material was shape-set to be straight and was super-elastic prior to embedding (Austenite finish temperature above room temperature). Super-elastic fibers were selected due to available material supply. Welding was performed with a 7 micron Ra surface roughness sonotrode on 101.6 mm by 76.2 mm (4″ by 3″) Al 6061-T6 base plates near 4.76 mm (0.1875″) in thickness. The base plates were constrained with a custom metal matrix composite fabrication fixture and vacuum chuck. Foils with a width of 23.81 mm (15/16″) and a thickness of 0.152 mm (0.006″) were utilized. The welding parameters used in this study are listed in Table 1. These parameters were chosen from a statistical optimization study for UAM-welded Al 6061-H18 material [15].

Table 1
Ultrasonic welding parameters used in this study.

Parameter	Value
Temperature	22 °C (70 °F)
Force	6000 N
Amplitude	32.76 μm (70%)
Speed	84.6 mm/s (200 in/min)

To embed a fiber, a ball end mill was utilized to cut a slightly oversized pocket to aid in fiber placement and encapsulation. The pocket's depth was slightly less than the fiber's diameter to enhance frictional scrubbing, help promote consolidation, and minimize loads on the fiber. A similar 'no load' fiber embedding method has been presented [16]. Laser machining was not utilized in this study to minimize aluminum oxide formation in the fiber's pocket prior to embedding. To isolate a fiber, additional machining operations were alternated with welding and fiber encapsulation to ensure the embedded fiber was within a representative weld zone of the UAM process. After machining and welding, samples were removed with electrical discharge machining to minimize cutting stresses on the sample and achieve small sample dimensions. Final

[1] 6061-H18 foil as supplied by the vendor was fabricated by cold rolling 6061-O stock material to an H18 temper.