NDT and E International 93 (2018) 117–130

Contents lists available at ScienceDirect

NDT and E International

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

In-situ interfacial quality assessment of Ultrasonic Additive Manufacturing components using ultrasonic NDE

Venkata Karthik Nadimpalli [a,b,*], Li Yang [a], Peter B. Nagy [b]

[a] Department of Industrial Engineering, J.B. Speed School, University of Louisville, Louisville, KY 40217, USA
[b] Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH 45221, USA

ARTICLE INFO

Keywords:
UAM
NDE
Additive manufacturing
Imperfect interfaces
Inversion
Bond quality

ABSTRACT

Ultrasonic Additive Manufacturing (UAM) is a layer-by-layer solid-state fusion process that bonds thin metal foils on top of a base substrate by using ultrasonic vibrations. In this study, longitudinal mode ultrasonic nondestructive evaluation (NDE) was used to assess the bond quality of UAM components. An interfacial spring model was developed to predict wave propagation through layered media, and the results verified by finite element simulation. Two independent interfacial stiffness coefficients are required to model the experimentally observed principal signals, one for the base/build interface (η_1) and one for the rest of the layers in the UAM stack (η). An inversion model was proposed to estimate η_1 and η from experimental signals. Sensitivity analysis shows that the inversion is robust even with random variations introduced into the simulated signals. With sufficiently large number of layers, it was demonstrated that a Floquet wave homogenization using the inverted interfacial spring stiffness accurately predicts the experimentally observed phase velocities. In-situ layer by layer bond quality inversion results were presented for three components of varying quality. The results of this study pave the way for utilizing ultrasonic NDE to measure the quality of UAM interface layers both in-situ and offline.

1. Introduction

UAM is a layer-by-layer metal-based solid-state bonding process which is commonly used in conjunction with a Computer Numerical Control (CNC) mill. In this process, ultrasonic energy is utilized to create solid-state metallurgical bonding between a thin foil and an existing flat substrate. CNC machining after depositing each layer is performed to achieve required shapes and dimensions, enabling a freeform fabrication. The additive-subtractive nature and the low-heat solid-state processing give the UAM process certain unique capabilities such as completely enclosed internal cooling channels, smart parts with embedded sensors, metal-matrix composites, and bonding metallurgically incompatible dissimilar metals [1,2]. UAM involves high-speed scrubbing between foils to be joined. Several researchers have studied the mechanism of bonding both experimentally as well as through simulation [3–5]. The bonding process is a function of the three principal input parameters; force applied, velocity of bonding, and vibration amplitude. It has been shown to be dependent on surface roughness, temperature, base plate characteristics, part geometry, and build height [6–8] among other factors. Traditionally, UAM utilized an ultrasonic welder of 20 kHz frequency with maximum power limit of 3 kW. Recent integration of higher power (up to 9 kW) ultrasonic welders gave UAM the capability to weld more materials [7].

Bond formation by ultrasonic welding requires two conditions to be fulfilled, (i) the generation of clean surfaces with no barrier layers at the atomic scale and (ii) a direct contact between these clean surfaces which facilitates diffusion and hence a metallurgical bond. Electron Backscatter Diffraction (EBSD) studies [4,5] have shown that between any two foils the microstructure can be divided into upper bulk region, fine grained interface region, and lower bulk region. The most common defects in UAM components are classified as Type 1 defects which are delaminations between layers and Type 2 defects which form between adjacent tracks that are out of the scope of this study. Type 1 defects that can be seen via optical microscopy are gross delaminations and indicate process parameters which are far away from optimal that would never be used in a typical industrial setting.

Process parameter optimization within UAM has typically been performed experimentally by varying the three input parameters until a satisfactory bond quality was achieved according to the metric of Linear Weld Density (% of area that appears to be fully bonded via optical microscopy). Some researchers [4] have found that %LWD is not a good measure of the bond strength since it does not consider kissing bonds or

* Corresponding author. Department of Industrial Engineering, J.B. Speed School, University of Louisville, Louisville, KY 40217, USA.
E-mail address: knadimpalli18@gmail.com (V.K. Nadimpalli).

https://doi.org/10.1016/j.ndteint.2017.10.004
Received 6 February 2017; Received in revised form 8 October 2017; Accepted 11 October 2017
Available online 13 October 2017
0963-8695/

tightly closed regions. A better qualitative mechanism was suggested [3] based on a pull out tensile test followed by measurement of the fractured surface to analyze the % bonded region. It was argued that there is a definite presence of tightly closed surfaces in UAM that cannot be observed with an optical microscope, since only after tensile testing will these kissing bonds be visible. It was further explored how there could be what appears to be complete metallurgical bonding but on pull out tensile tests along the build direction the measured UTS could be as low as 15% that of a solid wrought material [3]. The reasoning for the same was argued to be the presence of micro-voids that form upon the application of a small amount of stress. These voids predominantly occur at the interface and coalesce into cracks leading to brittle fracture. Within the literature on bond strength measurement in UAM, mechanical tests involved using lap shear, push-pin, and tensile tests [8–10]. It is of primary interest to be able to identify those imperfect interfaces which are often invisible even to a high-magnification optical microscope. UAM aluminum components are essentially transversely isotropic due to the interface imperfections between the layers. The strength along the other two directions was shown to be roughly equal to around 80% the UTS of wrought material [3]. The quality of bonding at each interface determines the overall component stiffness. Since UAM was developed for producing end-use functional parts, it is beneficial to monitor the process online to enable closed loop control of the process. While the strength of UAM components depends on the weakest interface where failure occurs, it is beneficial to monitor the stiffness of each layer.

The existing online monitoring literature on UAM is primarily based on temperature measurement [11]. Usually, an infrared (IR) camera is used to observe the temperature of the just bonded foil during welding. The weld energy is calculated as a function of the rise in temperature and correlated to the peel strength of the welds. Another method to monitor temperature is to embed a K-type thermocouple between two UAM layers and bond on top of the same. A truly online monitoring approach has been demonstrated with a photonic Doppler velocimeter measuring the phase and velocity of the sonotrode, foil, and base [12]. This method has shown some promise in characterizing the contrast between a good weld and a poor one, but monitors only the just bonded foil. Online in-situ monitoring of layer-by-layer manufacturing processes offers a unique advantage which is to adjust the build parameters in real time to achieve closed loop process control. Most fusion based AM processes form defects in the top few layers from the solidification zone and hence monitoring the top surface is critical, leading to the use of optical techniques such as IR imaging. But in the case of UAM parts, a layer might be fully bonded initially but can form a delamination due to repeated cyclic loading several layers after it has been bonded. This makes it crucial to have a monitoring process that goes through the component. This, coupled with the lower temperatures in UAM, makes it an attractive candidate for ultrasonic NDT.

Micro-voids, kissing bonds, and tightly closed interfaces produced by the UAM process can be treated as interface imperfections. In a seminal paper, Baik and Thompson described how the interaction of ultrasonic waves with an imperfect interface could be modeled as a spring-mass system when the wavelength of ultrasound was large in comparison to the size of the interface [13]. Nagy showed how imperfect interfaces in similar and dissimilar inertial and friction welds could be characterized by ultrasound and introduced a method to differentiate between different kinds of imperfect interfaces like slip bonds, kissing bonds, and partial bonds based on their different normal-to-transverse interfacial stiffness ratios [14,15]. Several researchers have shown ultrasonic techniques to be effective in classifying adhesive, diffusion and friction welded bonds [16–18]. UAM components consist of a layered structure with several imperfect interfaces and each interface is like diffusion bonded/friction welded interface. Hence, ultrasonic methods are naturally the first choice as a potential NDE technique. There exist several efforts on using NDE techniques to certify Additively Manufactured components [19,20]. Many of them are aimed towards powder bed fusion processes, and present different kinds of defects and interface imperfects compared to UAM [21]. A similar NDE sensor setup has been developed by Reider et al. for the laser melting AM process [22,23].

The current study is aimed at developing a robust, sensitive ultrasonic NDE technique that can be used for bond quality inversion of UAM components. For this purpose, the most sensitive technological parameter, the vibration amplitude is varied and the quality of the resulting components is studied. In Section 2 preliminary results from an in-situ online monitoring study are presented, followed by the results of a qualitative offline NDE test conducted on a set of UAM components and a discussion of the effects of having an NDE sensor during UAM component fabrication [24]. Section 3 discusses modeling of a layered UAM component as a base plus stack (set of layered interfaces) such that each interface between layers is modeled as a distributed spring. An analytical model for wave propagation through UAM components is developed and verified through finite element simulations in COMSOL. Further, due to the repeating nature of the system a Floquet wave homogenization model is developed for phase velocity and impedance prediction. It is shown that at least two independent variables, namely base/build interfacial stiffness (η_1) and average stack interfacial stiffness (η), are necessary to represent wave propagation through UAM components. Section 4 presents an inversion algorithm determining interfacial stiffnesses η_1 and η from the measured ultrasonic signals. Correlation between experimentally measured mechanical strength versus ultrasonic velocity is established and the sensitivity of the inversion model is studied. Three components with varying quality were tested using the in-situ monitoring setup to demonstrate layer by layer inversion of bond quality. Finally, in Section 5 conclusions are drawn from the obtained results and directions for future work are suggested.

2. Experiment

Fig. 1 shows an in-situ monitoring setup that was designed to be used during the UAM process. The base plate has been lifted by supports to accommodate an ultrasonic transducer that is in contact with the base plate using high-temperature grease as couplant. 150 μm layers of annealed and heat treated aluminum alloy Al6061 H18 are bonded directly on top of the Al6061 T6 base plate. It is important to keep in mind industrial applicability while designing a monitoring system that can be used during processing real components. Several challenges were faced as the design was iterated and changed from monitoring from above to monitoring from below the base plate. Choosing an appropriate coupling medium was important along with the choice of having a thin layer vs. larger volume of couplant. The adverse effects of introducing a transducer below the base plate on stack quality have been studied though not presented in this work. Being aware of all these parameters, the design was iterated to what is shown in Fig. 1. The dimensions of base plate, transducer, supports and the UAM layers are indicated in the figure. To nondestructively evaluate UAM parts it is necessary to build a set of components with varying qualities and study the sensitivity of quality assessment. Of the three principal technological parameters of the UAM process (weld force, weld speed, and vibration amplitude), it is well known that build quality is most sensitive to vibration amplitude variations. A preliminary study was performed on a manual Fabrisonics R200 research system on which the in-situ monitoring setup was installed such that ultrasonic data is collected after bonding each layer. Six vibration amplitudes ranging from 25 to 35 μm were used to build 45 layers at a weld force of 5000 N and weld speed of 70 mm/s.

A broadband longitudinal contact transducer of 5 MHz nominal frequency was driven using a JSR Ultrasonics DPR 500 remote pulser/receiver module. The data acquired was sent into a 1.5 GHz 14-bit Acquisition Logic PCI digitizer for processing. A 500 V pulse was used to drive the transducer with a damping of 50 Ω at a pulse repetition frequency of 200 Hz. 16 such waveforms are collected and averaged to produce a single point A-scan after bonding of each layer. 16 waveforms were used for each point A-scan to increase SNR. The processed raw data was then exported to and analyzed in MATLAB. The average group delay