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Process improvements and characterization of ultrasonic additive manufactured structures

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ABSTRACT

Ultrasonic additive manufacturing (UAM) is a solid state joining technology that produces metal parts and components at low temperatures by utilizing principles of ultrasonic metal welding. The process can produce solid and gapless structures, however under certain processing conditions voids and poor mechanical properties may occur. Builds wider than the foil width require stacking of foils next to and on top of one another, leading to the potential for voids, while also requiring periodic machining to maintain flatness. This study proposes a methodology to improve the bonding and mechanical properties of Al 6061 UAM builds. Specifically, the stacking sequence of foil layers, the effects of surface roughness during welding and following machining, and post-process heat treatments are examined. An optimized stacking sequence for foils has been identified via mechanical strength testing, whereby tape to tape overlap should be greater than 0.0025 in. (0.0635 mm) using a randomized layer stacking sequence. Sonotrodes with a 14 μm R_a surface roughness are shown to provide improved bond quality compared to sonotrodes with 7 μm roughness. Welding onto surfaces roughened with the sonotrode after flattening passes has also shown to improve bond strength. Post-process heat treatments increase the bond strength over as-built conditions, providing strengths close to 90% of bulk material.

1. Introduction

Ultrasonic additive manufacturing (UAM) is a solid state joining technology that uses ultrasonic vibrations developed by piezoelectric transducers to join thin metal foils. The ultrasonic vibrations operate around 20 kHz, generating a scrubbing action at the mating interface of a prospective joint through contact with a horn or sonotrode, as described by White (2003). This scrubbing action combined with a normal force creates local plastic deformation, collapses asperities, and displaces oxides and contaminants, which according to Graff (2005), leads to nascent metal surfaces and bonding. The process is conducted in a continuous rolling action where successive foils are joined on top of or next to a previously bonded layer.

UAM systems are often integrated into a CNC framework used for subtractive milling operations, in addition to the additive stage associated with welding. Using the additive and subtractive stages in tandem, UAM can be used to create unique geometries or integrated channels for thermal management devices or other such components, as exhibited by Norfolk and Johnson (2015) producing cooling devices. UAM is a low temperature process, with operating temperatures below 50% of the melting temperature of aluminum, as shown by Sriraman et al. (2010). Because it is low temperature, UAM is a proven method of creating composite structures with embedded components such as smart materials and electronics which would otherwise be damaged in high temperature thermal joining processes. Examples include embedding shape memory alloy (SMA) fibers in aluminum by Kong et al. (2004), creation of active composites with shape memory alloy fibers by Hahnlen and Dapino (2014), embedment of fiber optics by Kong and Soar (2005), and embedding temperature sensitive sensors into metallic structures by Siggard (2007). Additionally, the low temperature nature of the process allows for joining of dissimilar materials without generation of detrimental intermetallics. Examples include Al–Ti combinations exhibited by Hopkins et al. (2010), Al–Cu by Truog (2012), Al–steel, and many other combinations by Obielodan et al. (2010).

Process parameters commonly controlled during welding operations include normal force, oscillation amplitude, and rolling speed. These weld parameters can have a significant influence on bond quality, with an optimal value for each parameter varying depending on the materials being joined. For example, Hopkins et al. (2010) identified that normal force and weld speed are significant for Al–Ti combinations while studies by Wolcott et al. (2014)

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and Hopkins et al. (2012) indicate that amplitude and weld speed are significant for Al–Al combinations. Recent advances in the available ultrasonic power for welding from 1 kW to 9 kW demonstrated by Graff et al. (2011), have increased the capacity for normal force to be applied during welding, while maintaining a given oscillation amplitude. This power increase enables joining more material combinations and increased the potential designs for welded joints. Moreover, Fujii et al. (2011) have shown that the increase in available power has led to a strong decrease in voids within UAM builds. Typical welds with Al 6061 using the 9 kW process require 2 kW of ultrasonic power for strong joints.

Current UAM equipment can create parts on the order of several feet on each side, limited only by the currently available table dimensions. In taking advantage of the full dimensions of this build envelope, detrimental effects to weld quality due to structural compliance and resonance phenomena must be considered. Robinson et al. (2006) have shown that the increased compliance of free standing structures as build height increases leads to a lack of surface deformation required for bonding. Hehr et al. demonstrated that less mechanical power is applied when compliance increases and propose an approach to compensate for this effect (Hehr et al., 2016). Gibert et al. (2010) have shown that at specific height to width ratios, structural resonances can become excited leading to a lack of relative motion of work pieces and poor bonding.

Wider builds can remedy these issues, however they require abutting tapes next to one another, which in turn creates a source for void formation, as exhibited by Obielodan et al. (2010). Overlapping of tapes can minimize or prevent void formation at the abutments, but the build surface becomes less flat and uniform due to accumulation of material at the seam locations. An example of a UAM build exhibiting poor flatness and accumulation of material at the seams due to tape overlap is shown in Fig. 1. Periodic flattening passes conducted regularly throughout the build using the CNC stage in state of the art UAM systems can remove this material. However, inhomogeneities are created within the build because some layers are welded onto surfaces textured by the sonotrode, while others are welded onto a smoothly machined surface. Consequently it is necessary to understand the effect welding onto smooth and textured surfaces has on bond quality.

The purpose of this paper is to outline investigations performed to improve the UAM process for aluminum 6061 material. Improvements addressed in this paper include the interrelated issues of tape overlap and roughness, as well as investigation of post-process heat treatments which have been shown to improve material properties. Section 2 describes the relevant research problems in detail, with previous work and potential methods of addressing them. Section 3 describes a study on the optimal overlap and stacking sequence of foils. In section 4 the effect of surface roughness on the UAM process is investigated, examining the roughness of sonotrodes for welding as well as the effect of welding onto smooth or roughened surfaces. Section 5 describes a study on the effect heat treatment has on UAM Al 6061 tensile properties through testing as-built, annealed, and samples aged to the T6 condition. All work performed in this study used a 9 kW Fabrisonic SonicLayer 4000 UAM system. The system is fully automated and includes CNC milling capabilities.

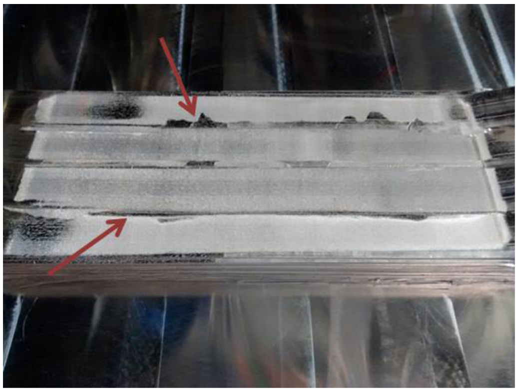

Fig. 1. Block build showing thickness variations at seam locations with arrows indicating areas of material accumulation.

2. Background

To minimize void formation at tape abutment points and improve bond quality, an overlap can be utilized when welding tapes next to one another. A schematic of this overlap concept is shown in Fig. 2, where tapes are laid on top of one another at the abutment and the potential void is filled in via plastic deformation. Tape stacking or stagger is shown in Fig. 2 as the variable distance between abutment joints of successive layers. If the tape joints are all aligned at the same location in the UAM build, localized void concentration and the risk of cracking along this seam increases. Utilizing a brick-like stagger pattern between successive layers can minimize crack formation and void concentration within the build. Previous work conducted by Obielodan et al. (2010), studied the effect of tape overlap and stagger of successive Al 3003 foils on bond quality for 1 kW UAM. A similar study needs to be performed on 9 kW UAM, investigating whether differences in material build up occurs at seam locations and whether a new overlap and stacking scheme is required for 9 kW UAM.

Surface texture or roughness has been shown to play an important role in UAM. Li and Soar (2009) showed that a rougher sonotrode surface in 1 kW UAM produced improved interlaminar bonds due to improved energy transfer (2009). However, a rougher sonotrode surface created more voids at the weld interface due to insufficient plastic deformation of the larger surface asperities. Related work by Friel et al. (2010) in 1 kW UAM indicated that an optimal roughness for joining may exist to create strong bonds

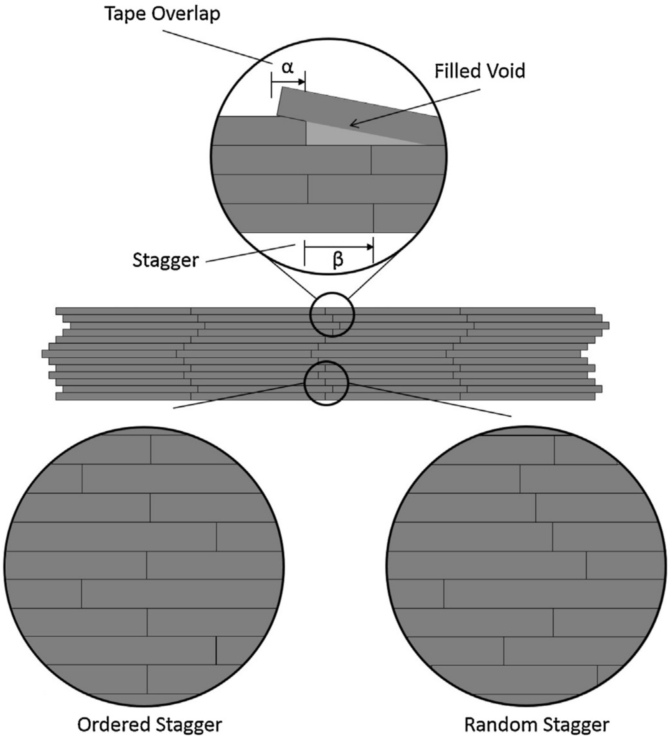

Fig. 2. Tape overlap and stagger, i.e., stacking sequence, with potential void filled in via plastic deformation of the tape.