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Elastic constants of Ultrasonic Additive Manufactured Al 3003-H18

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ABSTRACT

Ultrasonic Additive Manufacturing (UAM), also known as Ultrasonic Consolidation (UC), is a layered manufacturing process in which thin metal foils are ultrasonically bonded to a previously bonded foil substrate to create a net part. Optimization of process variables (amplitude, normal load and velocity) is done to minimize voids along the bonded interfaces. This work pertains to the evaluation of bonds in UAM builds through ultrasonic testing of a build's elastic constants. Results from ultrasonic testing on UAM parts indicate orthotropic material symmetry and a reduction of up to 48% in elastic constant values compared to a control sample. The reduction in elastic constant values is attributed to interfacial voids. In addition, the elastic constants in the plane of the Al foils have nearly the same value, while the constants normal to the foil direction have much different values. In contrast, measurements from builds made with Very High Power Ultrasonic Additive Manufacturing (VHP UAM) show a drastic improvement in elastic properties, approaching values similar to that of bulk aluminum.

1. Introduction

Ultrasonic Additive Manufacturing (UAM), also known as Ultrasonic Consolidation (UC), is a new manufacturing process in which metallic parts are fabricated from metal foils. The process uses a rotating cylindrical sonotrode to produce high frequency (20 kHz) and low amplitude (20–50 μm), mechanical vibrations to induce normal and shear forces at the interfaces between 150 μm thick metallic foils [1]. The large shear and normal forces are highly localized, breaking up any oxide films and surface contaminants on the material surface, allowing for intimate metal-to-metal contact. As the Ultrasonic Consolidation process progresses, the static and oscillating shear forces cause elastic–plastic deformation and a high dislocation density. The deformation also leads to high localized temperatures through adiabatic heating. The presence of high temperatures and a high dislocation density may trigger recrystallization and atomic diffusion across the interface, leading to a completely solid-state bond [2–4]. This process is repeated, creating a layered manufacturing technique, which continuously consolidates foil layers, to previously deposited material. After every few foil layers, CNC contour milling is used to create the desired part profile with high dimensional accuracy and appropriate surface finishes [5] (see Fig. 1).

The mechanical properties of UAM components are measured using a few testing methods. Peel tests are the most widely used mechanical test as they require only a few consolidated layers (1–3 foil layers), minimal machining and use of a standard mechanical test frame. Peel tests adhere to British Standard EN 2243-2:1991 and involve consolidating foil layers on top of one another with the top most foil being bonded along only half of its length. The top foil layer is then peeled away from the other consolidated foils using a mechanical test frame. Ideally, fracture involves progressively fracturing small colonies of bonded areas along the bonded interface, slowly peeling the interface apart until the entire bonded interface is separated. This test gives the user an interfacial failure load, but often failure occurs through the foil thickness revealing little about the interfacial bond. The interfacial failure load from peel tests can be used to determine optimal UAM process parameters, but cannot be used as a design criterion [6–9].

Traditional tensile and shear tests are also used to evaluate UAM samples. In studies performed by Schick et al. [10] on consolidation of Al 3003-H18, tensile tests revealed that the ultimate tensile strength of UAM samples, with the tensile load oriented in the rolling direction, is 17% greater than monolithic aluminum. Tensile tests with the load orientated in the transverse direction (thickness direction of the foil), revealed that the ultimate tensile strength is 86% less than monolithic aluminum. This suggests that when a UAM component is loaded so that all the interfaces are in the load path (as in the tensile tests in the transverse direction), the strength of UAM components is greatly reduced due to the presence of interfacial voids. Hopkins et al. [11] performed a DOE and statistically characterized the significance of process parameters on the ultimate tensile and shear strength of Al 3003-H18 UAM builds. It was found that vibrational amplitude and normal force

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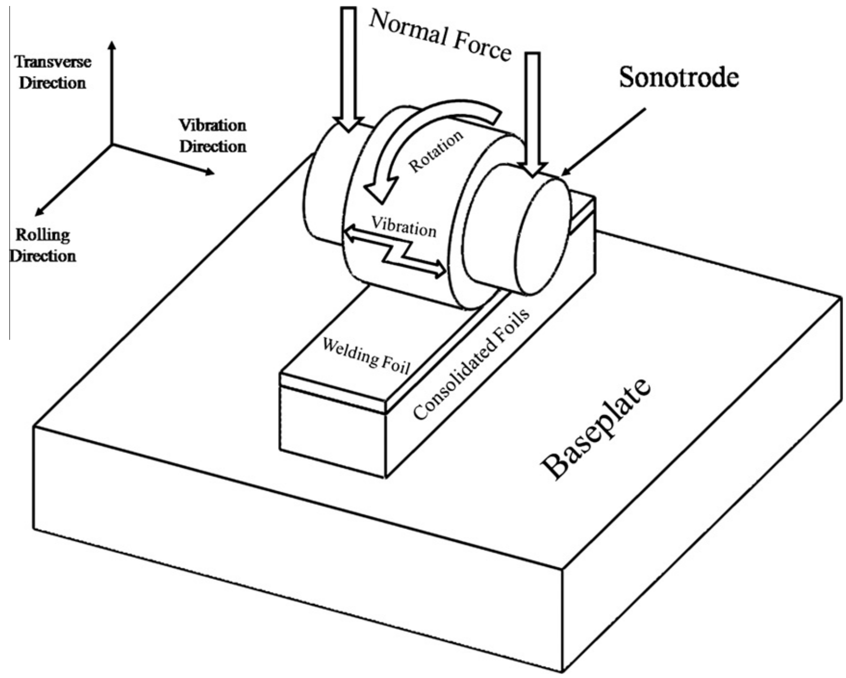

Fig. 1. Schematic of UAM process.

have a strong effect on interfacial bond strength, while welding speed has a relatively weak effect. Even though both Hopkins et al. and Schick et al. performed traditional tensile tests, strain data was not collected; therefore, elastic properties of the UAM specimens were not determined.

The push-pin test is another mechanical test used to evaluate UAM failure load and stiffness. Push-pin tests involve consolidating 16 layers on top of a metal base plate. A hole is then drilled from the bottom of the baseplate through the entire baseplate into the first few foil layers of the UAM build. Then a hardened steel pin is pushed through the stationary baseplate, applying force normal to the consolidated foil, eventually causing delamination or shearing through the foil layers. This method allows for mechanical testing using only a few deposited layers and gives the user a force vs. displacement curve. The push-pin test measures mechanical properties only in the transverse direction and reveals nothing about properties in the vibration and rolling directions. Research by Zhang et al. [12] reported that, because voids are present, the failure loads recorded were much less than with monolithic aluminum and that failure loads increase with increases in bonded area. They also found that the slope of the force vs. displacement curves changed depending on the process parameters, but could not explain why this was occurring.

Although UAM samples were tested using various mechanical testing techniques, macroscopic three-dimensional elastic constants were not determined. Accurate values for elastic constants are needed for modeling the substrate and foil dynamics during consolidation. Modeling of the UAM process has been done by Huang and Ghassemieh [13] as well as Zhang and Li [14]. These authors assume isotropic properties of UAM builds, similar to that of bulk metals, in their models. The isotropy assumption is invalidated by the presence of planes of voids along the bonding interfaces. Prior research has shown that the failure strength of a UAM part depends on the testing direction with respect to foil orientation due to the presence of interfacial voids. Thus, it is likely that interfacial voids not only have an effect on failure strength, but also have an effect on the elastic properties of UAM components. Therefore, the current research focuses on the measurement of the elastic constants in the three material directions (rolling direction, vibration direction and transverse direction) and the characterization of how interfacial voids affect these elastic constants.

To provide context to the current research, a brief review of factors that can lead to a change in the elastic constants of materials is presented below. Considerable change of elastic constants can occur in a material for a number of reasons. Luo and Stevens [15] showed that the Young's and shear moduli of 3Y-TZP ceramics were negatively affected by porosity (e.g. 75% reduction for 38% porosity volume). Kim and Bush [16] demonstrated that decreasing grain size as well as increasing volume fraction of porosity had a negative effect on elastic modulus in Fe, Cu and Pd (e.g. 60% reduction in elastic modulus for 30% porosity volume in Fe). Substantial porosity in these polycrystalline materials had the most prevalent effect on Young's modulus while grain size had a negligible effect unless grain sizes became less than 20 nm. Weertman et al. [17] found that elastic moduli decreased by 66% in nanocrystalline Pd. UAM does not lead to large nanocrystalline regions and therefore, we believe that the microstructure may not have a large effect on elastic constants.

Elastic constants can be measured by mechanical testing. However, due to the small geometries of these builds and lack of yielding, this approach is difficult. In the literature, ultrasonic testing has been used to measure stiffness in the three material directions. Blessing and Bertram [18] used ultrasonic velocity measurements to prove that elastic modulus as well as shear modulus of Al-Alumina composites decrease with porosity. Jeong et al. [19] used ultrasonic testing to determine elastic constants in silicon carbon reinforced aluminum. Thus ultrasonic testing can be used as an alternative to mechanical testing to give accurate elastic constants.

Measuring wave velocities in a material can be used to determine elastic constants. In Fig. 2 side-to-side motions parallel to the incident plane indicate shear wave propagation into the plane. The motions normal to the plane indicate longitudinal wave propagation into the plane. The velocity of each wave is dependent on the material density and directional stiffness. Note the direction coordinate system in which axis-1 is the sonotrode rolling