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Mechanism of weld formation during very-high-power ultrasonic additive manufacturing of Al alloy 6061

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Abstract

The microstructures of Al alloy 6061 subjected to very-high-power ultrasonic additive manufacturing were systematically examined to understand the underlying ultrasonic welding mechanism. The microstructure of the weld interface between the metal tapes consisted of fine, equiaxed grains resulting from recrystallization, which is driven by simple shear deformation along the ultrasonically vibrating direction of the tape surface. Void formation at the weld interface is attributed to surface asperities resulting from pressure induced by the sonotrode at the initial tape deposition. Transmission electron microscopy revealed that Al–Al metallic bonding without surface oxide layers was mainly achieved, although some oxide clusters were locally observed at the original interface. The results suggest that the oxide layers were broken up and then locally clustered on the interface by ultrasonic vibration.

Keywords: Ultrasonic additive manufacturing; Ultrasonic welding; Aluminum alloy; Recrystallization; Oxide layer

1. Introduction

Ultrasonic additive manufacturing (UAM) is a novel solid freeform fabrication process that utilizes the ultrasonic seam welding technique to merge metallic layers [1]. This process directly produces metallic components from a 3-D model by successive welding of layer after layer on a substrate material. The resultant components can be formed according to the desired accuracy and geometry by computer numerically controlled (CNC) machining during the UAM process. Since the process works well with metals having low deformation resistance [2,3], there are high expectations that the range of applications of the UAM process can be extended to fields such as rapid prototyping, low-volume tooling, metallic cladding and embedding of materials. Specific examples include injection molding dies, parts with embedded channels, incorporation of second-phase material, and other components with complex geometries, which are difficult to produce through conventional manufacturing techniques. Compared with conventional techniques, the UAM process offers the following main advantages:

(i) Since the temperature of the metallic tapes is raised only up to 30–50% of the melting point of the base metals, thermal distortions of the fabricated components are small [3].
(ii) Control of the atmosphere, molds, and/or degreasing of the tape surfaces are not required. Therefore, it is possible to reduce manufacturing costs and environmental burdens.
(iii) The high cycle times of the deposit and trim leads to great productivity.

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Therefore, the UAM process has great potential as a useful tool for environmentally friendly and cost-effective metal-forming technology. However, the nature of the ultrasonic welding between the metal tapes during the UAM process is not yet fully understood.

In earlier researches on the UAM process, the ultrasonic welding parameters have been optimized for Al alloys [2,3]. The key processing parameters in UAM, which strongly affect the quality of the fabricated components, are the frequency and amplitude of the ultrasonic vibration (typically 20 kHz and 5–26 μm, respectively), the applied normal force (0.5–2.0 kN), the travel speed of the sonotrode (up to 50 mm s^{-1}), and the texture of the sonotrode surface (4–15 μm r_a). The quality of the components has been often evaluated by the linear weld density, which is defined by the ratio of the welded to the total interface length at a selected cross-section. Kong et al. developed a process window of the UAM process on the basis of the weld strength obtained by peel tests [2,3]. Ram et al. examined the effects of the processing parameters on the linear weld density and discussed void formation at the weld interface during the UAM process [4]. They suggested that the surface roughness of the tape induced by the sonotrode played a major role in void formation. According to these works, the quality of UAM components was remarkably improved by increasing the ultrasonic amplitude and the normal force. UAM using a high amplitude and normal force is currently known as very-high-power (VHP) UAM [5,6].

Some works on the characterization of the microstructure around the weld interface have recently been conducted to understand the physical and chemical processes of ultrasonic welding during the VHP-UAM process [7–9]. For welding of metallic materials in the solid state [10–18], it is well known that two requirements must be fulfilled: (i) generation of clean surfaces with no barrier layers at the atomic scale; and (ii) direct contact between these clean surfaces [4]. Ram et al. [4] suggested on the basis of fundamental examinations of the UAM process that surface-oxide layers are broken up during ultrasonic welding and displaced in the vicinity of the interface region in Al alloy 3003. Moreover, it is proposed that the deformation at the interface breaks the surface-oxide layers that inhibit metallic bonding between the metal surfaces [4]. Dehoff et al. examined the interfacial microstructures of UAM-produced Al alloy 3003 components by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) [8]. They observed a distribution of discontinuous oxide in the vicinity of the interface by SEM. TEM observation revealed the presence of oxide layers inside of voids and remaining at the interface after UAM, although detailed knowledge on the behavior of the oxide layers is difficult to find. Furthermore, other studies have proposed that some metallurgical phenomena at the weld interface, such as recrystallization [9] and plastic flow [19], significantly contribute to the ultrasonic welding mechanism during the UAM process. Although some studies on the ultrasonic welding mechanism have been reported, as mentioned above, direct evidence for metallic bonding at the weld interface between the tapes is missing and the contribution of metallurgical phenomena to the welding mechanisms in the VHP-UAM process is still unclear. Systematic studies on the fundamental welding mechanism in the VHP-UAM process are necessary for the further development of the UAM technique. The aim of the present work is to understand the ultrasonic welding mechanism during the VHP-UAM process by means of systematic examinations of the microstructures near the interface between the tapes, with special focus on deformation, recrystallization and the behavior of the oxide layers at the interface.

2. Experiments

A VHP-UAM component was prepared using tapes of commercial Al alloy 6061-H18. The tapes, 150 μm thick, were successively stacked until 31 layers were affixed to a baseplate of Al alloy 6061. The approximate dimensions of the component were 24.5 mm (width) × 170 mm (length) × 4.65 mm (height). The coordinate system of the specimen is defined in terms of the accumulating direction (AD), the vibrating direction (VD) and the rolling direction (RD), as shown in Fig. 1. The VHP-UAM process was conducted without any external heating with the following processing parameters: 20 kHz frequency, 31 μm vibrational amplitude, 5.6 kN normal force, and 35.6 mm s^{-1} sonotrode travel speed. The sonotrode was cooled to room temperature with each cycle. The specimens were cut from the component and mounted in conductive resin. They were ground with SiC abrasive paper in water and then polished with diamond paste. Finally, a surface suitable for microstructural observations was prepared in a colloidal silica solution on a Buehler VibroMet vibratory polisher.

The microstructural observations and electron backscatter diffraction (EBSD) analyses were performed with field-emission gun-scanning electron microscopes (Hitachi S-4300SE and JEOL JSM-7800F). The weld interfaces at

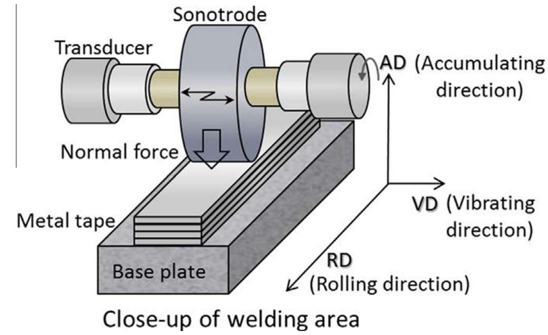

Fig. 1. Schematic of the UAM process and definition of the respective directions.