Scripta Materialia xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Scripta Materialia

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

Viewpoint article

High-strain-rate deformation in ultrasonic additive manufacturing

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ARTICLE INFO

Article history:
Received 18 August 2016
Received in revised form 13 December 2016
Accepted 21 December 2016
Available online xxxx

Keywords:
Ultrasonic additive manufacturing
Ultrasonic welding
Al alloy 6061
High-strain-rate deformation
Plastic flow

ABSTRACT

High-strain-rate deformation in ultrasonic additive manufacturing was analyzed by performing microstructural characterization via electron microscopy. The micro-asperities on the top tape surface, which were formed by contact with the sonotrode surface, underwent cyclic deformation in the shear direction at high strain rates during welding with an additional tape. This caused plastic flow and crushing of the micro-asperities, and a flattened interface was formed between the upper and lower tapes. Further, surface oxide films were fractured and dispersed by ultrasonic vibration, and metallurgical welding was achieved.

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Ultrasonic additive manufacturing (UAM) is a novel metal forming technology based on ultrasonic welding of metallic tapes [1,2]. Ultrasonic vibrations typically of 20 kHz frequency are applied parallel to the weld interface through a sonotrode under a static normal force. Since the ultrasonic welding of metals is a solid-state process, solid-phase metallurgical phenomena, such as plastic flow, friction between tapes, and high-strain-rate deformation around the weld interface, are key factors to be considered for realizing sound welds between successive tapes in UAM [2–10]. In the early stage of weld formation, micro-scale asperities on the surfaces of tapes facing each other at the interface were preferentially deformed, and plastic flow across the interface is initiated. The high friction and the plastic flow between the tapes have been considered to fracture the oxide films at the weld interface, promoting nascent metal-metal contact and eventual metallurgical bond formation [11–13]. The sonotrode surface is usually textured so as to facilitate gripping of the tape subjected to vibrations. The resultant rough imprint on the tape surface affects bonding of the subsequent layer. With the progression of accumulative processing, severe deformation at high strain rates and deformation heating occur around the weld interface [14–16]. Although the above phenomena caused by high-strain-rate deformation would significantly affect the weld formation and interfacial microstructure evolution [17–29], a few studies have focused on detailed characterization to investigate the effects [2,13,29].

In order to provide context, a brief summary of the previous studies that focused on the high-strain-rate deformation in ultrasonic metal welding is presented below. Gunduz et al. reported that the high-strain-rate ($\sim 10^3$ s^{-1}) plastic deformation in ultrasonic welding of pure Al to pure Zn could increase the instantaneous vacancy concentration up to $\sim 10^{-1}$ [30]. Further, this strain-induced excess vacancy concentration drastically enhanced the diffusivity of Zn into Al by 1.9 μm^2/s, which was five orders of magnitude higher than the bulk diffusivity at 513 K. Panteli et al. clarified the effects of high-strain-rate deformation on intermetallic reaction in the ultrasonic welding of Al 6111 alloy to Mg AZ31 alloy [31]. They concluded that the generation of large excess vacancy concentrations by the high-strain-rate deformation primarily affected the early nucleation stage of the interfacial reaction. Thus, these phenomena based on the high-strain-rate deformation can promote weld formation during ultrasonic welding process. Although, welding mechanisms are not exactly the same between the UAM and ultrasonic welding processes, it is important to have an in-depth understanding of the deformation behavior around the weld interface in the UAM process. Therefore, characterization of the weld interface is essential to overcome the current lack of scientific knowledge regarding the deformation behavior. The aim of the current work is to develop a basic understanding of the role of high strain rates in the weld formation and microstructural evolution in the UAM process.

A multilayer build was prepared using tapes of commercial Al alloy 6061-H18 in this study. The tapes with a thickness of 150 μm and a width of 24.5 mm were successively stacked to form 31 layers on the Al 6061 base plate. The processing parameters for the UAM in this study were 20 kHz frequency, 31 μm vibrational amplitude, 5.6 kN normal force, and 35.6 mm/s travel speed of the sonotrode without any external heating. The direction of ultrasonic vibration was perpendicular to the travel direction of the sonotrode. The specimen cross-sections were obtained by cutting along vibrating direction-normal direction (VD-ND) plane to observe the interfacial microstructure.

The interfacial microstructure was observed by transmission electron microscopy (TEM). Small specimens for TEM were extracted from the interface region of the UAM build by the focused-ion beam (FIB)

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http://dx.doi.org/10.1016/j.scriptamat.2016.12.030
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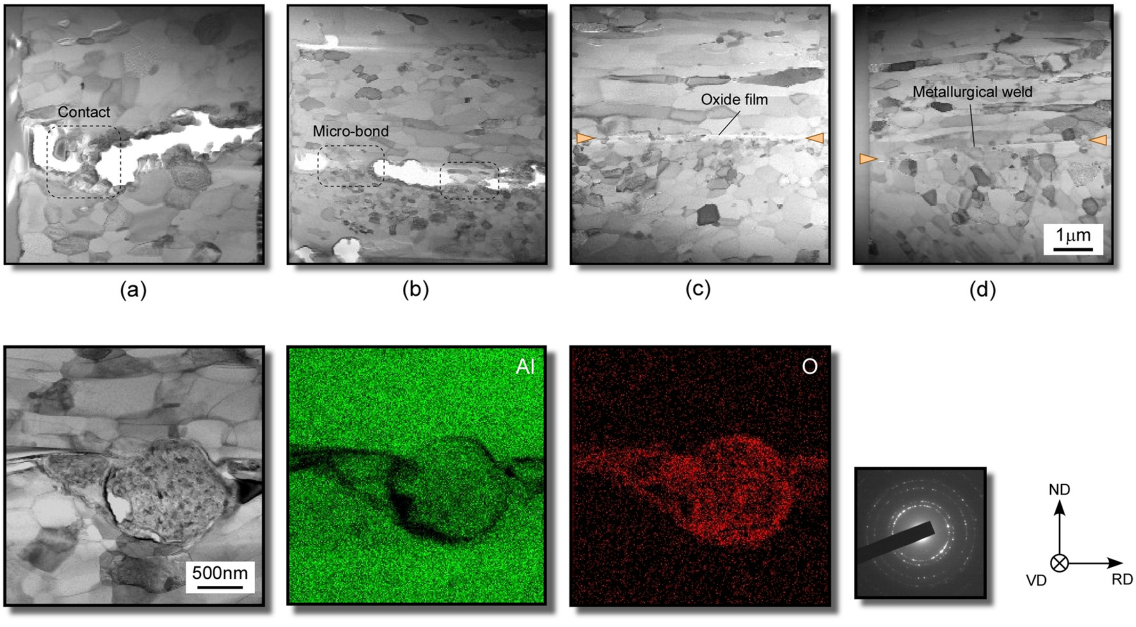
micro-sampling technique. Oxide films at the interface were identified by electron diffraction and TEM/energy-dispersive X-ray spectroscopy (EDS). In order to characterize the microstructures, electron backscatter diffraction (EBSD) analyses were also performed with field-emission scanning electron microscopy (FE-SEM). The electron beam scanning was carried out at step sizes of 0.05–0.2 μm on the VD-ND plane.

To understand the fundamental phenomena related to the weld formation process during UAM, the unwelded and welded regions were observed by TEM. The unwelded and partly welded regions are at the middle of weld formation because the contact between upper and lower tapes is not achieved and the phenomena related to the weld formation are not fully processed. Therefore, the observation of these would promote a more accurate understanding of weld formation process. Fig. 1 shows the bright-field TEM images obtained from the (a) unwelded region, (b) partly welded region, (c) welded region with residual oxide layer, and (d) completely welded region in the UAM build. In addition, the bright-field TEM image of a cluster found at the weld interface and the corresponding Al and O elemental maps are shown in Fig. 1(e). These illustrate how the metallurgical weld developed during UAM process. Fig. 1(a) shows the remaining asperities in contact with each other in the interfacial void. In the early stage of the UAM process, many micro-asperities on the top-most surface of the UAM build come in physical contact with the bottom surface of the additional tape. These micro-asperities are then compressively deformed owing to applied normal load during the ultrasonic vibration, and the resulting fracture of the oxide films on the micro-asperities causes the generation of micro-bonds. Fig. 1 (b) shows one example of the deformed micro-asperity and micro-bond formed between the micro-asperities. Once the micro-bonds are generated, the micro-asperities begin to cyclically move with the ultrasonic vibration of the additional tape. Subsequently, the micro-asperities are softened and crushed during the high-strain-rate deformation due to the ultrasonic vibration parallel to the weld interface, which is known as acoustic softening [32,33]. Thus, the interface is flattened, resulting in a large area of contact between the upper and lower tapes at the interface (Fig. 1 (c)). Although some amount of oxide films still remain at the weld interface at this step, with the expansion of the bond region, the films break and get dispersed around the interface owing to friction and plastic flow. In our previous work, the broken oxide films were found to appear as almost round clusters with some nanosized fcc aluminum particles as shown in Fig. 1 (e) [13]. These clusters with 1 μm diameters were distributed randomly at the weld interface. By the dispersion of oxide films, direct contact between newly formed Al surfaces is achieved and Al-Al metallurgical weld is formed over a large area (Fig. 1(d)). Moreover, recrystallization driven by deformation heating occurs around the surface of the lower tape. Consequently, the original grains elongated by rolling were replaced by newly developed fine equiaxed grains with <1 μm diameters.

The EBSD analyses were undertaken in order to gain a deeper understanding of the microstructural characteristics and deformation behavior around the weld interface and a void. The microstructural characteristics around the void would clarify the phenomena occurring during weld formation when the contact between upper and lower tapes is not achieved. For comparison, the microstructure of (a) the original tape and (b) top surface of the UAM build are first shown in Fig. 2. The grains were elongated along the rolling plane of the as-received tape in both specimens. At the top surface of the UAM build shown in Fig. 2(b), micro-asperities formed during the UAM process because of contact with the sonotrode (surface roughness $r_a = 7$ μm). As can be seen in Fig. 2(c), the typical fcc rolling texture was observed, as in the case of the original tape. By contrast, the {100} ⟨011⟩ texture was observed for the top surface of the UAM build (Region B in Fig. 2(b)). This is attributed to the compressive deformation resulting from the normal load due to the sonotrode. The micro-asperities on the top surface of the UAM build would effectively facilitate the formation of sound welds with the additional tape because they are preferentially deformed during the UAM process. Therefore, the surface texture of the sonotrode, which determines the characteristics of the micro-asperities, is also a significant factor in the UAM process. This indicates that the deformation of micro-asperities in the lower tape plays a key role in weld formation, which must be discussed as distinguished from the weld formation in ultrasonic welding. Fig. 3 shows (a) an image quality map, (b) an inverse pole figure map around a void and the weld interface, and (c) {111} pole figures for the various regions shown in the image quality map. The approximate location of the interface between the Al tapes is represented by a white dashed line in the



(a) (b) (c) (d)

(e)

Fig. 1. Bright-field transmission electron microscopy (TEM) images of the (a) unwelded region, (b) partly welded region, (c) welded region with residual oxide film, and (d) completely welded region. (e) Bright-field TEM image of a nanosized cluster observed at the weld interface and corresponding Al and O elemental maps obtained by energy-dispersive X-ray spectroscopy (EDS) analysis. The coordinate system of the specimens was defined by normal direction (ND), vibrating direction (VD) and rolling direction (RD).

Please cite this article as: H.T. Fujii, et al., High-strain-rate deformation in ultrasonic additive manufacturing, Scripta Materialia (2016), http://dx.doi.org/10.1016/j.scriptamat.2016.12.030

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