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Research Paper

Influence of tool edge angle on the bondability of aluminum in ultrasonic bonding

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ABSTRACT

A transitional stage in the relative motion was confirmed through in-situ observation using a high-speed camera and digital image correlation. In the earlier bonding time within the first 20 ms, relative motion predominantly occurred between the bonding materials, resulting in the formation of an initial bond at the bonding interface. The initial bond developed toward the vibration direction with increasing bonding time. The formation of a larger bonded region was observed at larger edge angles, resulting in greater joint strength. In the latter stage of bonding time beyond 50 ms, the relative motion between the tool edge and the bonding material became predominant because of bond formation at the bonding interface. The relative motion between the bonding tool and the bonding material caused macroscopic plastic flow in the bonding part when larger edge angles were used, leading to the observed increase in joint strength. The enhancement of bond creation at larger edge angles is discussed on the basis of finite element analysis focusing on the change in stress distribution at the bonding interface with the penetration of the tool edge.

1. Introduction

Ultrasonic bonding is a solid-state bonding technique characterized by its capability to join sheet metals and wires with less energy consumption and a shorter bonding time than other bonding methods. Recent interest in this technique has been stimulated in various applications such as joining thin films for electrodes of battery cells, dissimilar joining of automotive body panels, and additive manufacturing using multilayered foils. The principle of ultrasonic bonding is that the bonding interfaces are brought into close contact by a normal force and a high-frequency vibration is applied to the faying surface, leading to bond formation. To understand the bonding mechanism, which is essential to optimize the bonding condition, numerous researchers have investigated the interfacial phenomena at the bonding interface. Krzanowski and Murdeshwar (1990), who investigated the deformation process at the bonding interface for Al wire bonding, have shown that a recrystallized microstructure induced by thermomechanical effects of local shear deformation and a temperature rise is formed at the bonding interface. In the initial stage of bonding, a microbond is formed on the faying surface by interfacial friction through mechanical removal of contamination; the microbond spreads in the contact surface as the oxide layer is squeezed out (Maeda et al., 2013). In addition, Elangovan et al. (2008) performed finite element analysis for the deformation of bonding materials and showed that interfacial friction and the shear deformation cause the temperature rise. The temperature rise leads to growth of the weld microstructure in the latter bonding stage. The initially formed microbond expands in the vibration direction involving fracture of the oxide film at the bonding interface, resulting in material flow around the weld interface (Bakavos and Prangnell, 2010). Dehoff and Babu (2010) also observed the recrystallized zone around the bonding interface of multilayered aluminum alloy foils in ultrasonic additive manufacturing. Furthermore, Fujii et al. (2011) used electron backscatter diffraction (EBSD) analysis to confirm that the initial bond develops with shear deformation by the vibration.

The aforementioned interfacial phenomena are associated with friction at the bonding interfaces, which arises from the relative motion between the bonding metals. However, because the vibration is applied to the faying surface via a bonding tool attached to the ultrasonic horn, the friction often occurs at the tool surface in contact with the welding metal. Thus, the relative motion behavior that includes the tool and the bonding materials is also an essential factor for understanding the ultrasonic bonding mechanism. Our previous relative motion analysis using a high-speed camera observation for the ultrasonic bonding of AA1050 (Sasaki et al., 2013) clarified that relative motion occurring between the tool and the bonding material causes the temperature rise, resulting in enhancement of macroscopic material flow of bonding material. The importance of relative motion behavior in the bonding mechanism was also demonstrated by Lu et al. (2016) through a

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relative motion analysis using photonic Doppler velocimetry. The surface of the bonding tool, which is closely related to the friction between the tool and the bonding metal, is generally machined into a knurled surface with grooves or pyramid-like edges to suppress slippage between the bonding tool and the bonding materials. However, the penetration of knurled edges occasionally causes severe damage to the bonding part, leading to diminished joint strength.

The influence of the tool geometry on the bond characteristics has been reported by several researchers. Lum et al. (2006) and Jahn et al. (2007) discussed the effect of the knurl edge pattern on joint performance, associating the joint performance with the microstructure. In addition, Watanabe et al. (2010) revealed that the joint strength can be improved by using a tool with a cylindrical surface. Takahashi et al. (2012) conducted finite element analysis for the plastic deformation of bonding material during the bonding of Al ribbon. Although their analysis was limited to a microscopic area, it revealed that stress concentration occurs near the contact end of the tool edge with the bonding material, which enhances microbond formation on the faying surface. Furthermore, in a previous paper focused on the effect of knurl edge patterns on the microstructure (Komiyama et al., 2016), we pointed out that the angle of the tool edge influenced the relative motion between the tool and the welding material and thereby influenced the resultant weld microstructures. However, the relationships among the tool geometry, the relative motion behavior, and the resultant bond structure are not completely understood.

In the present study, we investigated the effect of tool edge geometry on the ultrasonic bonding performance, mainly focusing on the edge angle. We analyze the relative motion using a high-speed camera and correlate the relative motions between the bonding tool and the bonding materials, including the vibration and the edge penetration, to the joint strength and weld microstructure to understand bond formation during bonding.

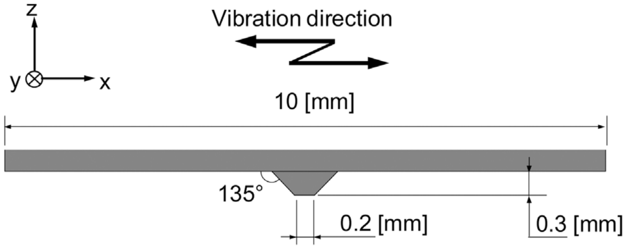
2. Experimental procedure

2.1. Bonding test

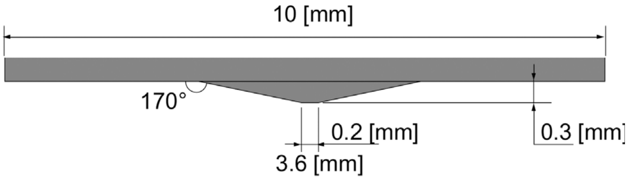
Industrial pure aluminum alloy (AA1050-H24) sheets with thicknesses of 0.5 mm and 3 mm were used for bonding experiments. The sheets were cut into coupons of 35 × 11 mm^2 and 40 × 20 mm^2, respectively. For high-speed camera observations, one end of the specimen was polished with #240 abrasive paper. An ultrasonic bonder with a power of 1200 W and a driving frequency of 21 kHz was used in this study. The vibration amplitude of the horn was 31 μm (peak-to-peak) under the no-load condition. Weld tools with a cross section of 10 mm square were machined on the tip of the ultrasonic horn. Three types of edges, as shown in Fig. 1, were prepared for the experiments. The external edge angles, θ, were 135°, 170°, and 175°. Here, the edge angle of $\theta = 135^\circ$ corresponds to the angle of a knurled edge generally used for ultrasonic bonding. The width of the edge tip that first contacts the bonding specimen and the height of the edge were 0.2 mm and 0.3 mm, respectively.

The 3-mm-thick specimen (lower specimen) was placed on a flat anvil and clamped by a fixture to suppress slippage (Fig. 2). The 0.5-mm-thick specimen (upper specimen) was lapped on the lower specimen, and vibration was applied to the upper specimen by the tool edge under a normal force of 588 N. The time range for the vibration (bonding time, t) was 0–300 ms. A tensile test was conducted for the bonded joints processed into the shape shown in Fig. 3. The maximum load during the tensile test was defined as the joint strength in this study. For microstructural observation of the bonded interface, the specimen was cut parallel to the vibration direction at the center of the bonded area.

(a) $\theta = 135^\circ$



(b) $\theta = 170^\circ$



(c) $\theta = 175^\circ$

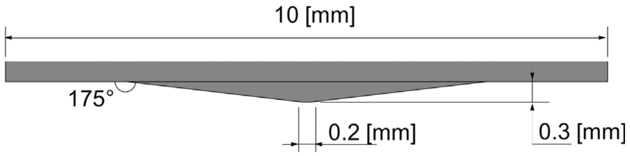
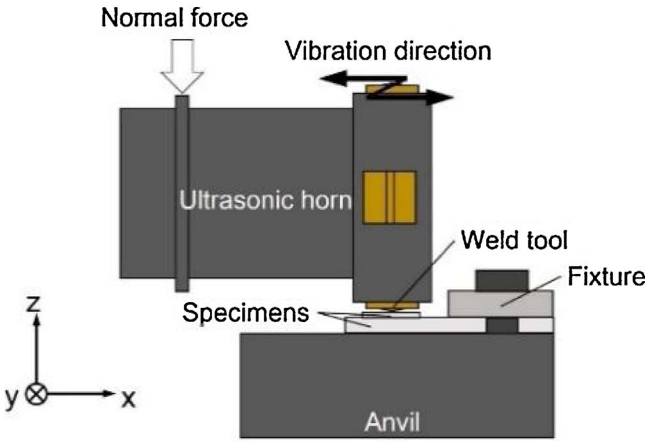


Fig. 1. Horn tip geometry.

Side view



Top view

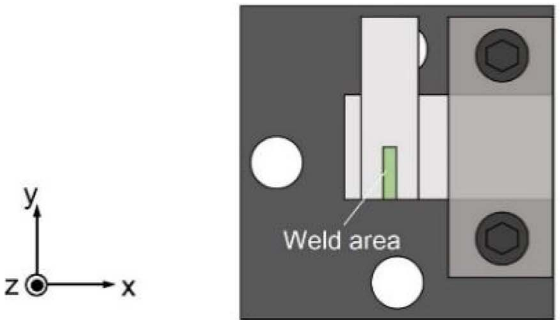


Fig. 2. Arrangement of specimens.