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Regular Article

Microstructure and lap shear strength of the weld interface in ultrasonic welding of Al alloy to stainless steel

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ABSTRACT

Dissimilar welds between Al alloy and stainless steel were produced with an ultrasonic welding technique. The weld strength increased with the welding energy. The welds produced with sufficiently high energy exhibited nugget pull-out failure of the Al alloy during the lap shear strength test. The welds with weld energies of more than 1.05 kJ fractured in the base metal and were severely deformed by the ultrasonic vibration, and recrystallization occurred around the weld interface owing to the shear deformation and heating during the ultrasonic welding.

Global environmental issues have led to a demand for increasing the mass efficiency of industrial products. One suggested solution has been the development of welding technology for multi-material design. Parts of conventional steel components are replaced with lighter materials through various dissimilar welding techniques to reduce the vehicle weight and improve fuel efficiency. The ultrasonic welding (USW) technique has been the subject of several studies because it can be used to achieve dissimilar welds between Al alloy and steel sheets with limited interface intermetallic reaction [1–3]. USW is a solid-state welding technique that is characterized by a lower energy input, a shorter welding time, and thinner workpieces than other welding techniques.

There have been several studies on USW to clarify the weld properties since it was first used to successfully weld metallic sheets together in the 1950s [4–8]. Many metallurgical phenomena around the weld interface have been found to significantly contribute to the mechanical behavior of the weld. Gunduz et al. welded 1100 H19 Al foil to a pure Zn sheet and revealed that the diffusivity of Zn in Al significantly increases around the weld interface during USW [9]. The estimated value of diffusivity was 1.9 $\mu m^2/s$, which is approximately 10^5 times higher than the normal lattice diffusivity. Additionally, they found that the phase stability changes around the weld interface owing to deformation-induced vacancies. Bakavos et al. used ultrasonic spot welding on 6111 Al automotive sheets and observed the material flow characterized by swirls of grains [10]. Many researchers have used the lap shear strength to characterize the mechanical properties of an ultrasonic weld [2,10–15]. In the tensile test, the fracture mode was found to change from interfacial debonding to nugget pull-out above a threshold welding energy.

Although many studies have been conducted on USW [16–36] in addition to the ones described above, knowledge on the dependence of the microstructure on the mechanical properties of the ultrasonic weld is limited. Moreover, there is currently little academic understanding on the welding mechanism of Al–steel USW despite its engineering significance and past research efforts [1–3,31]. The aim of the current work was to clarify the lap shear strength of the ultrasonic welds between Al alloy and stainless steel and the microstructural characteristics around the weld interface. The results can substantially contribute to the understanding of welding mechanisms involved in achieving sound ultrasonic welds between dissimilar metals.

This study used sheets of the commercial Al alloy 6061-T6 and 304 stainless steel sheets with dimensions of $50 \times 20 \times 1.0$ mm^3 and $50 \times 20 \times 0.5$ mm^3, respectively. The rolling direction (RD) of the specimens was set perpendicular to the direction of ultrasonic vibration. The shape of the horn tip was a square with 6 mm sides; thus, the welding area was approximately 6×6 mm^2. The surfaces of the ultrasonic horn and anvil were knurled to prevent them from slipping on the specimen surfaces. Table 1 lists the welding parameters used in this study. The welding energy of the table was estimated from the time integral of the welding machine power during USW. It exhibited a proportional relationship to the welding time. During USW, the temperature was measured by using a type-K thermocouple embedded on the interface between the Al alloy 6061-T6 and 304 stainless steel sheets.

To evaluate the weld strength of the specimens, a lap shear tensile strength test was employed at a crosshead speed of 3 mm/min. The tensile direction was set perpendicular to the direction of ultrasonic

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