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Microstructure, tensile and fatigue properties of ultrasonic spot welded aluminum to galvanized high-strength-low-alloy and low-carbon steel sheets

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ABSTRACT

The microstructure evolution, tensile lap shear strength and fatigue properties of dissimilar ultrasonic spot welded (USWed) joints of aluminum to two commercial steel sheets at different welding energies were investigated. The main intermetallics at the weld interface were θ ($FeAl_3$) in both joints along with eutectic Al-Zn in Al-to-galvanized high-strength-low-alloy (HSLA) steel joints and Fe_3Al in Al-to-ASTM A36 steel joints. The welding strengths of both joints were higher than those of other dissimilar joints reported in the literature. With increasing welding energy, the maximum tensile lap shear strength increased in the Al-to-galvanized HSLA steel joints, while the lap shear strength increased up to a peak value and then decreased in the Al-to-ASTM A36 steel joints. Both the average peak welding strength and fracture energy of the Al-to-galvanized HSLA steel joints were higher than those of the Al-to-ASTM A36 steel joints. The fatigue lives of both welded joints were in agreement with or somewhat longer than other Al-to-steel USWed joints in the literature. The fatigue fracture mode changed with increasing cyclic loads in both welded joints. Fatigue crack growth was mainly characterized by the formation of fatigue striations perpendicular to the fatigue crack propagation direction.

1. Introduction

In recent years, lightweighting in vehicles has become a crucial approach for improving fuel efficiency and reducing climate-changing CO_2 emissions [1,2]. The desire to find alternative solutions has driven the automotive and aerospace industries towards improving vehicle performance and fuel economy [2]. Hence, lightweight aluminum (Al) alloys have become increasingly popular in the fabrication of vehicles due to their high strength-to-weight ratio, good formability, machinability, environmental friendliness and recyclability [3–6]. Developing lower-cost joining techniques is key to expanding the use of Al alloys in auto body manufacturing [4], and the use of hybrid structures made by dissimilar joining techniques has now become necessary [7]. In recent years, multimaterial fabrication, especially the joining of galvanized high-strength-low-alloy (HSLA) steel sheets with competitive structural grades of Al alloys to reduce the overall vehicular weight has gained significant attention in the automotive industry [3,7]. Unlike high energy consuming resistance spot welding (RSW) (20 kWh) [4] and friction stir spot welding (FSSW) (2 kWh) [8], the welding of Al alloys using a USW process consumes less welding energy (~0.3 kWh per 1000 joints) [4,9,10]. Additionally, the peak temperature during USW does not surpass the melting point of the metal workpiece, eliminating the formation of undesirable compounds and metallurgical defects that are commonly observed in most other fusion welds [11]. USW is already considered to be an emerging and promising technique for joining non-ferrous metals and alloys (maximum sheet thickness of 1–2 mm) as well as welding dissimilar material combinations [4,12].

Previous studies have shown that one of the most detrimental issues during rapid solid-state welding process such as USW is control of the intermetallic compounds (IMCs) that form at the weld interface via an accelerated diffusion process [3,10,13]. These IMCs are brittle, and a continuous IMC interface layer severely deteriorates the joint strength [3]. For example, Haddadi [14,15] reported that the lap shear peak load decreased from 3.1 to 1.7 kN with increasing welding time due to an increase in brittle Fe_2Al_5 and $FeAl_3$ IMCs at the interface of Al to steel USWed joints. In addition, many studies have used interlayers or coatings to either inhibit their growth or avoid the formation of IMCs or form relatively ductile IMCs [12,13]. Watanabe et al. [13] used commercially pure Al sheet as an insert metal in the USW of Al-to-mild steel to study the effects of insert metals on joint

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properties. Patel et al. [3] and Haddadi et al. [12] have used zinc coated steel to inhibit/eliminate Al-Fe IMCs during Al-steel USW joining and showed improved mechanical properties. The composition of the weld materials can strongly affect IMC formation at the joint interface in dissimilar welding [16], although the relationship to many common alloy additions is still unknown. To the best of our knowledge, there are no systematic studies on the effect of interlayers on the formation of IMCs and the subsequent monotonic and cyclic properties of USWed dissimilar joints in the open literature. Many studies have reported squeezing of eutectic Al-Zn during USW of Al to Zn-coated steel [3,12]; however, its role in the mechanical properties of the joints has not yet been clearly understood. In addition, there is no information addressing any kind of comparison between USWed galvanized high strength low alloy steel and low carbon steel joints. The present study was, therefore, aimed at gaining a better understanding of the influence of interlayers on the formation of IMCs along with investigating the interface microstructures, tensile lap shear strengths and fatigue properties of two USWed dissimilar Al-to-steel joints.

2. Materials and experimental procedure

The USWed joints were produced using commercially available 1.5 mm thick sheets of Al 6061-T6 alloy and two commercial steels (a cold-rolled hot-dip galvanized HSLA steel and a low-carbon ASTM A36 steel). The nominal chemical composition of test materials used is given in Table 1. The sheet surfaces were ground using 120 grit sand paper, cleaned with ethanol followed by acetone, and dried before welding. The lap tensile test samples were welded in an energy mode using 15 mm×60 mm strips using a Sonobond dual-head spot welding system, with the weld located at the center of a 20 mm overlap. A transverse relative displacement between the sheets with the vibration direction perpendicular to the rolling direction was applied during USW. Welding was carried out at different welding energies ranging from 500 to 1750 J by varying the welding time (t) from 0.25 to 0.875 s at a constant power of 2 kW, an impedance setting of 8 and clamping pressure of 0.4 MPa. The welding energy is determined by the relation $Q \sim P\times t$, where Q is the weld energy and P is power, e.g., the weld time of 0.75 s at 2 kW power corresponds to ~ 1500 J of welding energy.

The metallographic samples were prepared from welded joints (sectioned across the center parallel to the direction of vibration in the wedge-reed system) using a slow-speed diamond cutter and then the sample preparation was done using standard metallographic techniques. Microstructure examinations were performed using a scanning electron microscopy (SEM, JEOL JSM-6480LV) equipped with energy dispersive X-ray spectroscopy (EDS). A computerized Buehler hardness testing machine was used for the microhardness tests on the polished surface in the vicinity of the interface using a dwell time of 15 s. Special attention was paid during the hardness tests to keeping adequate space to avoid any potential effect of the strain field caused by adjacent indentations. To estimate the joint strength, tensile lap shear tests were performed for each welding condition using a fully computerized United Mechanical Testing Machine at room temperature at a constant crosshead speed of 1 mm min^{-1}. As indicated above, both the lap shear tensile test and fatigue test specimens were 60 mm length and 15 mm width at 20 mm over lapped position. The total failure energy was calculated from the area under the load-displacement curve up to the peak failure load. Phase identification on both matching surfaces of the Al and steel was performed after the tensile shear tests using a PANalytical X-ray diffractometer (XRD) with Cu K_α radiation at 45 kV and 40 mA in back reflection mode. The diffraction angle (2θ) at which the X-rays hit the samples varied from 20 to 100°, with a step size of 0.05° and 2 s at each step. Load-control fatigue tests were performed in accordance with ASTM E466 on a fully computerized Instron 8801 servo-hydraulic testing system at different maximum loads. To avoid potential buckling of the test specimens, tension-tension cyclic loading at a stress ratio of R (P_{min}/P_{max}) =0.2 was applied at a frequency of 50 Hz with a sinusoidal waveform. At least two samples were tested at each energy level for both the tensile lap shear tests and the fatigue tests. To minimize the phase angle and the resulting bending moments of the specimens during the tensile lap shear and fatigue tests, two spacers or restraining shims were attached at both ends of the specimen. The tensile and fatigue fracture surfaces were examined via SEM.

3. Results and discussion

3.1. Microstructure evolution

For solid-state welded joints of dissimilar metals, there are two main factors controlling the joining performance [6]. One is the intimate contact between the dissimilar materials, and the other is the microstructure, particularly the formation of IMCs. In the present study, microstructural characterization was conducted on the cross-section of selected welded samples at various welding energy values (500–1750 J) to investigate the relationship between physical weld attributes and weld performance. Fig. 1 shows the microstructures of dissimilar USWed Al 6061-to-galvanized HSLA steel and Al 6061-to-ASTM A36 steel joints at different welding energy levels. As seen from Fig. 1, there were no large defects, such as cracks, voids or tunnels, present in the samples under most of the welding conditions, indicating overall good bonding under all of the welding conditions. It is apparent from the SEM images (Fig. 1(e) and (f)) that almost sound joints were achieved by increasing the welding energy up to 1500 J. Furthermore, it is seen from Figs. 1(c), (d), and (f) that interface bonding also occurred via mechanical interlocking due to solid-state deformation at higher welding energy levels of 1000–1500 J as well as the formation and progressive spreading of microwelds. This is related to the considerable increase in temperature in the weld zone, which softens the material and allows the sonotrode tips to sink into the sheet surfaces. In the process, the weld interface is displaced into complex wave-like flow patterns as indicated by the yellow dashed circles (Figs. 1(c), (d), and (f)). A similar phenomenon was also reported in Refs. [9,10,12,17]. It is also obvious from the SEM images of dissimilar USWed Al 6061-to-galvanized HSLA steel welds (Figs. 1(a), (c), and (e)) that an Al-Zn-enriched non-uniform layer was observed at the interface between the Al and Fe substrate under most of the welding conditions. The thickness of the Al-Zn layer increased with increasing energy input. At higher energy inputs (1000 J and 1500 J), the welded

Table 1
Nominal chemical compositions of the materials used.

			Chemical composition (wt%)										
Material	Mn	Si	Cu	Ni	Cr	Mg	Nb	Mo	C	S	P	Fe	Al
6061-T6	0.07	0.71	0.3	–	0.14	1.14	–	–	–	–	–	0.18	Bal.
HSLA	0.62	0.23	0.04	0.013	0.04	–	0.021	0.005	0.06	0.004	0.006	Bal.	0.04
ASTM A36	0.80	0.40	0.2	–	–	–	–	–	0.25	0.050	0.040	Bal.	–