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Formation of nanometer scale intermetallic phase at interface of aluminum-to-steel spot joint by welding–brazing process

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ABSTRACT

Interfacial microstructure, joint strength and crack propagation passage of fusion weld–brazed IF steel/Al 5754 joints were investigated. Nanometer scale intermetallic τ_5 compound layer and needle-like τ_6 ternary phase were observed at the interface with a heat input below 0.27 kJ/cm. Joint shear strength of 150–200 MPa was obtained, which resulted from the formation of an ultra-thin ternary intermetallic phase and the lack of the more brittle binary intermetallic phase at the steel/solidified filler alloy interface.

The formation of Fe_xAl_y-phases at the interface is necessary for achieving a metallurgical bond between the steel and the Al alloy. However, formation of an excess of Al-rich intermetallic phases will result in low strength and brittle joints. In order to minimize the intermetallic phase (IMP), solid-state welding such as friction stir welding has been considered. For example, Tsutomu Tanaka et al. [1] have reported the formation of a nanometer scale IMP layer during friction stir welding of A7075-T6 and a mild steel plate which corresponded with a very high joint strength. The solid-state welding can significantly reduce IMP thickness and improve joint strength, but is often limited to certain work-piece geometries and joint designs.

Compared to solid-state welding, fusion welding can often be much more flexible. Recently, a welding–brazing hybrid process has been developed to join steel to Al [2,3]. However, this process so far has been applied only to linear steel–Al joints. It is well known that spot welding in the automotive industry is of great importance. Resistant spot welding (RSW) is currently the most common joining method for steel body panels. Unfortunately it is difficult to apply RSW to weld aluminum and steel, as a thick IMP layer significantly reduces the joint performance [4].

Therefore it is desired to develop a reliable fusion spot joining process for Al–steel joining, which is able to produce a joint interface similar to that made by a solid-state joining process. This study focuses on the investigation of joining process feasibility, microstructure and mechanical properties of the welded spot joint.

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The base materials used were 2 mm thick aluminum alloy AA5754 and 1.8 mm thick galvanized interstitial-free (IF) steel with 10 μm thick Zn coating. Al–12Si wire was employed as the filler material. Before gas metal arc welding a 4 mm hole was made in the Al sheet, which, together with the steel sheets, was degreased with acetone. The spot welding process is schematically shown in Fig. 1(a). Welding speed was maintained at 200 cm/min. Two different wire feed speeds (WFSs) were used during welding, i.e., 215 cm/min from location 1 to location 2 and a variable wire feed speeds (225–350 cm/min) from location 2 to location 3.

After welding, cross-sections of joins were cut, ground and polished. A scanning electron microscope (Nova NanoSEM 650) equipped with an energy dispersive X-ray (EDS) analyzer and a transmission electron microscope (TEM, FEI's Tecnai Osiris) operating at 200 kV, equipped with a high angle annular dark field (HAADF) STEM detector and ChemiSTEM X-ray detection technology, were employed to characterize the IMP. In order to determine the joint strength, a cylindrical sample with a diameter of 3 mm was cut from the center of the joint (Fig. 1(a)). Shear testing was carried out using an Instron 8562 machine under a constant displacement rate of 1 mm/min. A specially designed jig was used for shear testing with the joint interface at the shear edge (Fig. 1(b)).

Fig. 2(a) shows SEM microstructure at the steel/weld interface made with WFS of 215 cm/min (heat input 0.18 kJ/cm). An ultra-thin and continuous compact plate-like IMP layer was observed along the interface. A TEM sample was prepared using a focused ion beam (FIB) microscope. Fig. 2 (b), (c) and (d) shows respectively STEM HAADF images at the interface, EDS mapping and selected area diffraction (SAD) pattern from the IMP layer. The IMP layer is ~250 nm thick, which contains Al, Fe and Si (Fig. 2 (c)). The chemical composition of the IMP layer was determined by quantitative EDS analysis to be 62.9–66.8 at% Al, 16.5–19.4 at% Fe and 10.2–10.4 at% Si. According to the Al–Fe–Si ternary phase diagram and characterization of the ternary solid phases in Al–Fe–Si system [5], the IMP layer was determined to be the τ_5-$Al_{7.2}Fe_2Si$ phase. It was confirmed by electron diffraction as evidenced by SAD patterns taken from the IMP layer (Fig. 2(d)).

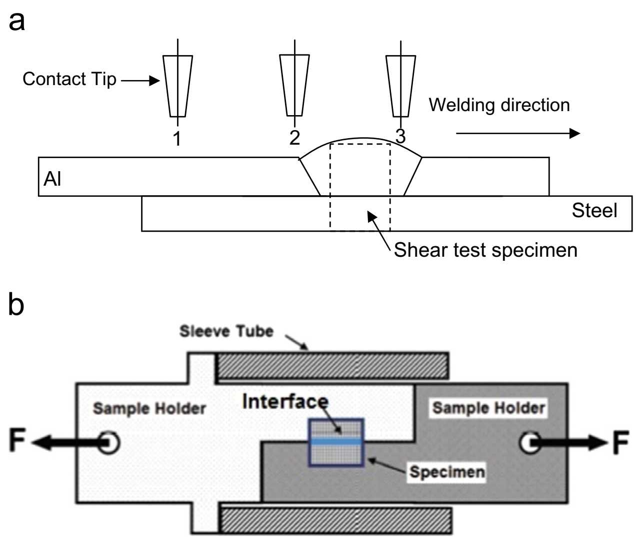

Fig. 1. Schematic drawings of GMAW spot welding of aluminum and steel (a) and shear test fixture (b).

Fig. 3 shows the interfacial microstructure of the joint produced with a WFS of 300 cm/min (heat input 0.27 kJ/cm). Two types of reaction products were observed. Type I was the same as the one observed in the previous joint made (Fig. 2). However, the IMP thickness was increased to 355–500 nm (Fig. 3(a)). In some regions a needle-like reaction product (type II) with a length of 0.7–3.0 μm and a width of 100–550 nm has grown into the weld metal, from the interface at the expense of the consumption of type I reaction layer (Fig. 3(b)). The chemical composition of the needle-like type II product determined by quantitative STEM EDS analysis was 57.2–68.6 at% Al, 13.7–15.4 at% Fe and 13.1–14.2 at% Si (Fig. 3(c)). SAD pattern confirmed that the needle-like type II product to be τ_6-$Al_{4.5}FeSi$ phase (Fig. 3(d)).

With a further increase of WFS to 350 cm/min (heat input 0.35 kJ/cm), the interface maintained the same characteristics as those of the one made with 0.27 kJ/cm heat input. However the type I IMP (τ_5-$Al_{7.2}Fe_2Si$) layer has thickened to 0.8–2.0 μm with small needle-like crystals oriented perpendicular to the interface, whereas the needle-like type II product has grown into longer ones with a larger aspect ratio.

As shown in Fig. 4 (a), the shear strength ranged from 150 to 200 MPa when heat input was below 0.27 kJ/cm. The joints made with heat input of 0.18 kJ/cm, fracture at the solidified filler

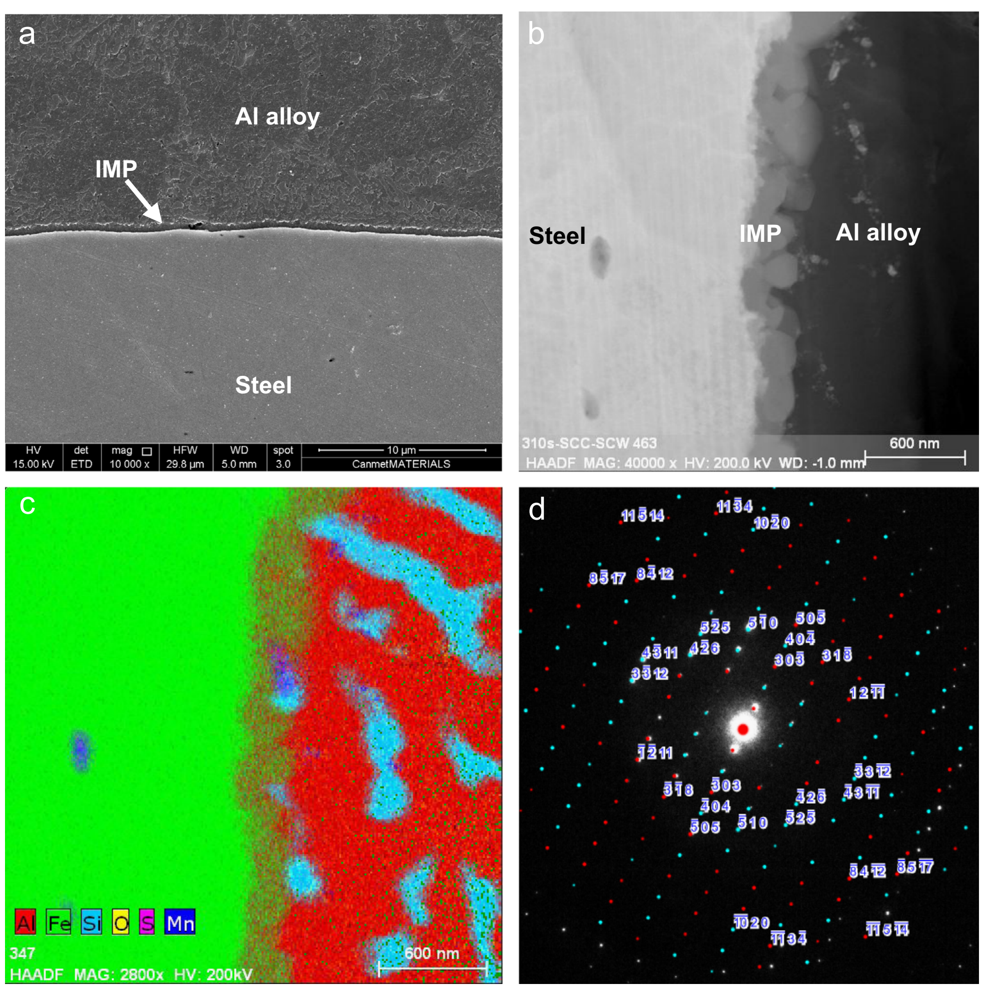

Fig. 2. Interfacial microstructure of a joint made with 0.18 kJ/mol. (a) SEM image; (b) STEM image; (c) EDX mapping and (d) indexed SAD from IMP showing [151] zone axis of τ_5-$Al_{7.2}Fe_2Si$.