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On the joining of steel and aluminium by means of a new friction melt bonding process

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A new lap welding process for dissimilar materials has been developed and tested for steel-to-aluminium joints. A simple cylindrical tool is rotated and translated over the top steel plate, leading to a transient partial melting of the bottom aluminium plate and the formation of intermetallic reaction layers of $FeAl_3$ and Fe_2Al_5 as thin as 2.5 µm. Lap shear tests of the welds show very good resistance with fracture mostly in the base materials.

Keywords: Friction stir welding; Dissimilar welding; Aluminium alloys; Steels; Mechanical properties

Assembling dissimilar materials within integrated structures is nowadays a stringent requirement related to improved performance. It is particularly the case for the transportation industry that needs to reduce the weight of structures while still improving their strength and crashworthiness. While efforts are carried out to continuously improve the mechanical properties of new steel grades up to levels unreachable by other materials, as in the case of advanced high-strength steels, Al alloys also present very interesting levels of specific strength that easily ensure lightweight structures, as demonstrated by their ever-increasing use in transport applications. Consequently, the need for an efficient technology to join steel and Al alloys arises in the automotive industry to ensure profitability and lightness of the vehicles in addition to efficient sealing of the joints.

The main difficulty in joining steel and Al alloys results from the large difference in their respective range of solid-state stability, but also from their large reactivity leading to the formation of brittle intermetallic layers at their interface [1–4]. As a consequence, conventional fusion welding, such as arc and laser welding for which both materials melt, are unsuitable for joining steel to Al alloys since the temperature that is reached causes interdiffusion and growth of large intermetallic reaction layers resulting in a brittle cast structure with poor mechanical properties [5,6].

Among the various solutions that have been proposed to reduce the heat input and thus to control the interface reactivity [7], solid-state processes are particularly efficient for welding dissimilar materials since the formation of an intermetallic layer at the interface may be avoided or reduced to acceptable values [2]. In diffusion bonding, the materials to be joined are put in intimate contact for hours under pressure and at a temperature below 70% of the lowest melting point. A transient liquid may sometimes be present owing to a eutectic reaction between the materials being joined [8]. However, the native Al oxide layer of Al alloys acts as a diffusion barrier and inhibits bond formation [2]. In order to break this oxide layer and activate the surface, the friction welding process is based on the movement of one piece relative to the other under compressive axial load, thus also involving shorter reaction times and higher temperatures (near the lower melting point) [3]. However, friction welding is mostly limited to rods and tubes since the relative movement is obtained by rotation.

Friction stir welding (FSW) is another solid-state joining process which has been widely investigated for welding dissimilar materials, in particular Al alloys and steel, in a butt-joint [1,5,9,10] or lap-joint [11,12] configuration. Some studies have also considered a third material

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with a lower melting point, such as Zn, to act as a filler metal between Al and steel [13] or to help in reducing the thickness of the intermetallic layer at the interface [14]. Although FSW is considered a solid-state technique, Chen et al. observed that, when working with materials with very different melting points (Al 6061 and AISI 1018 steel in their case), one should locally reach the lowest melting point, leading to a method that combines the effects of both fusion and solid-state welding [1].

The present study aims at reporting a new welding technique [15] suitable for assembling dissimilar metallic materials, such as Al and steel sheets, thus circumventing the drawbacks of previous techniques. After stacking and clamping the metallic sheets, with the high-melting point material on top, a non-consumable flat cylindrical tool is rotated and pressed on the upper surface of the stack as shown on Figure 1. The rotating tool then advances along the surface at a predetermined speed. Frictional heat is generated due to the intimate contact between the pressed rotating tool and the top sheet. In addition, plastic deformation occurs below the rotating tool, also contributing to the temperature increase [16]. The generated heat is transmitted to the bottom sheet through the top sheet, and if it is sufficient, the low-melting-point bottom sheet partially melts, forming a localized pool of liquid metal in contact with the upper sheet. In contrast to conventional fusion welding processes, the melting temperature of the low-melting-point material is only exceeded slightly and very locally, resulting in a semi-solid welding process. The technique is easily implemented since it does not require any shielding gas, unlike laser welding [6], or specific preparation of the metallic sheets. In addition, in comparison with conventional FSW, the pin-less tool results in less abrasion of the tool and the absence of a keyhole at the end of the weld. Another benefit of this new technique is that the advancing speed is significantly higher than in other Fe–Al welding processes [7,11–14] and one could even foresee speeds as high as 1 m min^{-1} being attained. Our process could also be considered for welding other combinations of metallic materials with different melting points.

In order to demonstrate the sequence of reactions while avoiding complex metallurgical issues, simple steel and Al grades were first tested. A microalloyed ultralow-carbon (ULC) steel with the composition (wt.%) 0.013C, 0.136Mn, 0.01Si, 0.005S, 0.0132P, 0.002Ti, 0.003Nb,<0.0008N was used as the high-melting-point material. Cold-rolled and annealed sheets 0.8 mm thick with a mean grain size of 13 μm were used. 1 mm thick Al 1050 or 2 mm thick Al 2024 T3 sheets were used as the low-melting-point material. Sheets were 250 mm long and 80 mm wide. The surfaces were cleaned with acetone prior to stacking and welding. A tungsten carbide tool 16 mm in diameter was tilted backwards by 0.5°. The welding machine was controlled in displacement while the rotation rate was set at 2000 rpm for the whole set of experiments. The advancing speed ranged from 100 to 700 mm min^{-1}.

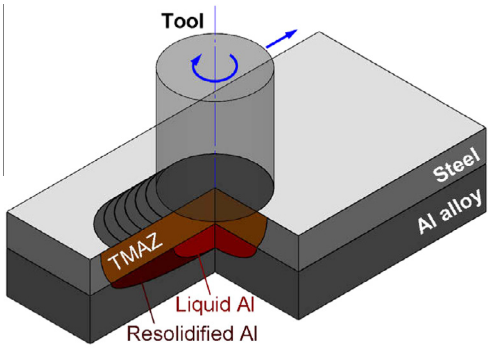

Figure 1. Schematic of the friction melt bonding process developed to assemble metallic sheets with different melting temperatures.

After welding, the joints were cross-sectioned by electrical discharge machining perpendicular to the welding direction for metallographic analyses and tensile testing. The transverse sections of the joints were observed by scanning electron microscopy (SEM) with back-scattered electrons (BSEs). In addition, the structure of the joints as well as the diffusion processes were characterized by energy-dispersive X-ray spectroscopy (EDX) and electron backscatter diffraction (EBSD). Transverse lap shear tests were performed on rectangular specimens with a width of 10 mm, at room temperature and with a crosshead speed of 1 mm min^{-1}. The recorded loads were normalized by the initial transverse section area of the sample at the fracture location, i.e. Al or steel sheets or lap-joints. SEM and EDX were also carried out on the fracture surfaces.

The typical microstructure of the joints is illustrated in Figure 2 in the case of the Al 1050–ULC couple welded at 400 mm min^{-1}. Three zones can be distinguished on the SEM micrographs, the Al and steel sheets being separated by a reactive layer. Close to the

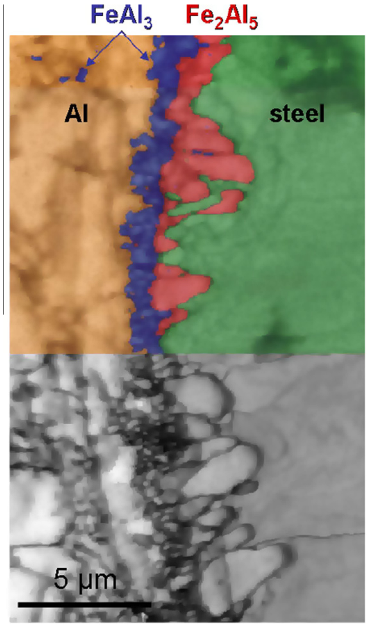

Figure 2. Typical band contrast EBSD map of the Al 1050–steel interface (advancing speed = 400 mm min^{-1}) with partial colouring as a function of the indexing phases (face-centred cubic Al in orange, monoclinic FeAl$_3$ in blue, orthorhombic Fe$_2$Al$_5$ in red and body-centred cubic Fe in green) which highlights the presence of two IMLs at the interface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)