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Friction stir weld assisted diffusion bonding of 5754 aluminum alloy to coated high strength steels

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ABSTRACT

In the present paper friction stir-induced diffusion bonding is used for joining sheets of 5754 aluminum alloy to coated high strength steels (DP600 and 22MnB5) by promoting diffusion bonding in an overlap configuration. Mechanical performance and microstructures of joints were analyzed by overlap shear testing, metallography, and X-ray diffraction. Our results show that the strength of joint is dependent upon tool travel speed and the depth of the tool pin relative to the steel surface. The thickness and types of intermetallic compounds formed at the interface play a significant role in achieving a joint with optimum performance. That is, the formation of high aluminum composition intermetallic compounds (*i.e.* Al_5Fe_2) at the interface of the friction stir lap joint appeared to have a more negative effect on joint strength compared to the presence of high iron composition intermetallic phases (*i.e.* FeAl). This is in agreement with previously reported findings that FeAl intermetallic can improve the fracture toughness and interface strength in Al/St joints.

1. Introduction

With the increased use of lightweight materials such as aluminum and magnesium alloys, the need for joining dissimilar materials is often required encountered. However, in order to achieve a combination of properties of both materials, it remains difficult to select effective welding processes for a given joint configuration. In the automotive industry, aluminum alloys are seldom used exclusively in a design, and so dissimilar aluminum/steel lap joining is of great interest since this is widely used in the assembly of parts (*i.e.* pillars, bonnets, door panels, and the trunk lids) [1]. It is estimated that a 25% weight reduction in sub-frames and about half the amount of energy will be required by using Al/St component instead of steel-made parts [2].

In processes involving potential interfacial reactions between aluminum and steel (*i.e.* welding, diffusion bonding, cladding, hot dip coating) the formation and growth of intermetallic compound layers is expected due to the limited solubility of Al in Fe. In dealing with inter-diffusion between aluminum and steel, the nature of the intermetallic compounds may be altered by specific time and temperature history and the presence of alloying elements which directly affect the mechanism of diffusion and hence kinetics of development and growth of the intermetallic phases. Therefore, improving the interfacial strength by controlling the intermetallic layers is of great interest. Several researchers [3–6] have reported the formation of different intermetallic compounds that are often occurred in the aluminum/steel joint interfaces (*i.e.* Fe_3Al, FeAl, $FeAl_2$, and Fe_2Al_5). It is clear that the types of formed intermetallic compounds and their thickness play a significant role in achieving a joint with optimum performance. It has been reported that the presence of intermetallic compounds with high aluminum composition (*i.e.* Fe_2Al_5) in the Al/St joint interface is particularly detrimental due to its brittleness [4,7]. However, Fe-rich compounds (*i.e.* FeAl) tend to exhibit slightly higher fracture toughness and interface strength in Al/St joints [4,8].

The application of solid state joining processes (*i.e.* friction stir welding) generally is associated with reduced formation of the intermetallic phases (compared with fusion welding processes) due to the lower temperatures and shorter times during the process. In particular, friction stir welding has effectively been used for joining different aluminum alloys to the coated and/or uncoated steels. Proper selection of friction stir welding parameters, *i.e.* tool geometry, rotation speed, travel speed, and penetration depth will control the microstructure and the interface bonding of the joint and will allow joining at relatively low temperatures with an overall short thermal cycle.

Since a controlling parameter in friction stir joints (*i.e.* lap configuration) between aluminum/steel sheets is the surface condition of the steel, some researchers [9–13] have adopted zinc-coated

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steels and reported successful joining of these to aluminum. Furthermore, from an industrial viewpoint, the application of coated steels (*i.e.* Zn coated) in the automotive body industries shows an increasing trend in the last two decades thanks to enhanced vehicle structure durability [13]. It has been proposed that Zn acts as a "lubricant" during friction stir lap welding by diffusing into the aluminum sheet and suppressing the melting point of the stirred material so that larger areas can be bonded [14]. Chen et al. [9–11] investigated the friction stir lap welding of an AC4C cast aluminum alloy and a low carbon Zn coated steel and reported that welding speed is the main parameter affecting the tensile properties and fracture location of the joints. In a further study, Elrefaey et al. [14] investigated the weldability of 1100 H24 aluminum alloy and uncoated and Zn coated steel in friction stir welding, and noted that the Al joints with Zn coated steel exhibited considerably higher fracture load as compared with those involving uncoated steel.

In addition to coating type, another critical factor in the joint strength in dissimilar aluminum/steel friction stir joining is the depth of the probe tip into the steel surface. Chen and Nakata [9], Elrefaey et al. [14], and Kimapong and Watanabe [15] all reported that the performance of dissimilar aluminum/steel joint depends heavily on the penetration depth of the friction stir welding tool into the surface of the lower steel sheet. All these studies noted that when the tool slightly runs into the steel surface, the joint strength is greater than that when the probe tip does not reach the steel surface. However, this also requires tool materials which are much higher strength than steel, such as carbide or other ceramics.

Imposing some pin penetration into the steel will promote the joint strength of Al/St friction stir lap welds, however, it is possible to use much lower cost tool material and still promote bonding via diffusion without penetrating the tool into the lower sheet of steel. This is particularly important to consider with ultra-high strength steels, such as 22MnB5 (also known as USIBOR® 1500-P), which exhibit strengths as high as 1500 MPa after hot stamping. In this case, little attention has been paid to this friction stir lap joining method when the tool is positioned so that the bottom of the pin is very close to or nearly in contact (without penetrating) with the lower steel plate. In the present paper, the effect of tool travel speed on diffusion bonding during friction stir welding is studied by assessing the interface microstructure evolution of an Al–Mg alloy (Al 5754) joined to coated high strength dual-phase steel (DP600) and ultra-high strength 22MnB5 grade steel. The microstructural features and overlap shear strength properties of friction stir welds are studied in detail when these two steels are used with different coatings (Zn versus Al–Si alloy coatings).

Table 1
Chemical composition (wt%) of the materials used for this study.

Material	Chemical composition
Al 5754	0.4 Si, 0.4 Fe, 0.5 Mn, 2.6–3.2 Mg, Al (bal.)
DP600	0.17 C, 0.8 Si, 2.2 Mn, 1.0 (Cr + Mo), 0.15 (Nb + Ti), 2 Al, 0.2V, 0.015 S, 0.08 P
22MnB5	0.22 C, 0.25 Si, 1.25 Mn, 0.16 Cr, 0.02 P, 0.008 S, 0.004 B, 0.015 Al, 0.035 Ti

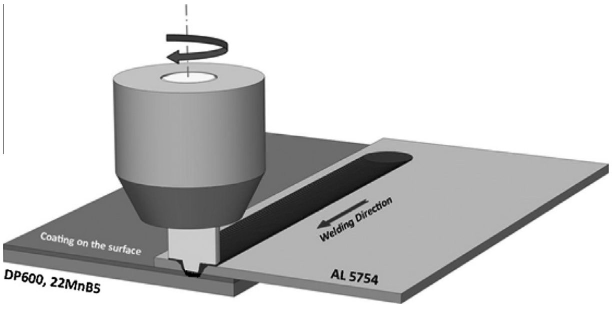

Fig. 1. Schematic illustration of FSW setup used in this study.

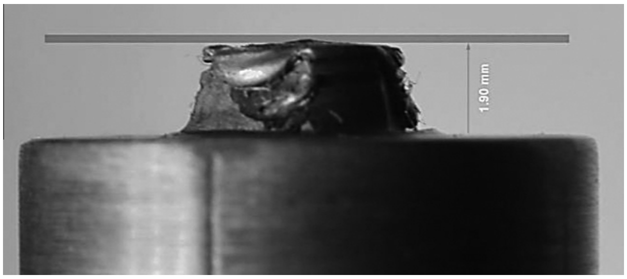

Fig. 2. Appearance of the torn tool after being pushed into steel sheet during FSW operation.

2. Experimental procedure

The base materials examined during friction stir welding were Al 5754 alloy with a thickness of 2.1 mm, dual phase DP600 steel with a zinc coating and thickness of 3.0 mm, and 1.5 mm thick 22MnB5 alloy steel with a 9 μm coating of Al–12Si alloy. Chemical compositions of tested materials are shown in Table 1. The sheets were welded in an overlap configuration with the aluminum alloy on top, and a stir tool made from H13 steel heat treated to 48 HRc was used. The welding tests were carried out using a modified milling machine, JAFO Model FWR40, with appropriate clamping, fixtures and machining settings.

Fig. 1 shows the schematic representation of the overlap friction stir welding setup used in this study. The tool had threaded pin geometry with 3 flats, with dimensions and speeds used as indicated in Table 2. The pin penetration depth was controlled so that the pin remained between 0.10 and 0.05 mm above the surface of the steel sheet. Initial trials showed that when the rotating pin is pushed into the steel plates, the welding could not be achieved because the rotating pin is worn out in a short duration, resulting in inadequate bonding between the sheets (Fig. 2). To prevent this, the pin was maintained above the steel sheet and this position was ensured using a digital readout with 0.005 mm resolution, and mechanical interlocks to prevent contact of the tool pin with the lower steel sheet. When the pin does not contact the steel plates, the amount of wear in the pin was negligible and this was verified by inspecting the tool pin using a stereo microscope after welding.

After welding, the joints were sectioned perpendicular to the welding direction for metallographic studies. The surfaces for observation of microstructure were etched using 2% Nital (HNO_3 and methanol) to reveal the steel microstructure and a Barker's re-

Table 2
FSW parameters used in this study.

Rotation speed (rpm)	Travel speed (mm/s)	Pin diameter (mm)	Tool shoulder diameter (mm)	Pin length (mm)
1800	16 and 45	4.0	12.0	1.9