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Role of welding parameters on interfacial bonding in dissimilar steel/aluminum friction stir welds

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ABSTRACT

In this study, lap welds between Al5754 to DP600 steel (aluminum plate top, and steel plate bottom) were manufactured by friction stir welding (FSW). The effects of welding parameters (*i.e.* travel speeds and penetration depth into lower steel sheet) on the interfacial bonding, tensile strength, and failure mechanism were investigated. The results show that intermetallic compound of Fe_4Al_{13} was detected at the Al/Fe interface. The weld strength increases significantly by increasing the penetration depth into the lower steel substrate at all travel speeds. The failure mode under overlap shear loadings is premature failure through the aluminum substrate when the penetration depth is more than 0.17 mm, and shear fracture when the penetration depth is less than 0.17 mm.

1. Introduction

The use of friction stir welding (FSW) for joining of dissimilar metals combinations in the automotive and manufacturing industries has been widely studied thanks to the fact that FSW offers a number of advantages for dissimilar materials, including: enhanced mechanical properties (*i.e.* tensile and fatigue), improved process quality, avoiding consumables, lower health and environmental issues, and reduced operating costs [1–3]. In the automotive industry, the focus on the application of FSW has mainly involved: the joining of extruded parts to form “larger extrusions”, sheet joining for tailor welded blanks, and joining of light-weight materials. FSW offers numerous advantages and potential for cost reductions in each of these cases. However, cost-effective and reliable joints between light-weight materials will demand significant development and further consideration. A compelling example of dissimilar FSW can be found in the 2013 Honda Accord, where this technique has been applied for joining the cast aluminum and stamped steel parts of the engine cradle [4–6]. In this case, a notable innovation is the use of a C-frame linear FSW system which exerts all the axial loading on the tool, thus avoiding the need for an extremely stiff and high load capacity robot and fixture to apply the tool force.

The main advantage common to nearly all the techniques is that solid state processing limits the temperature rise within the weld region. This limits the formation or growth of undesirable and brittle intermetallic compounds (IMCs) within the weld which deteriorate strength. Lower peak temperatures also minimize thermal distortion and residual stresses, which can often lead to the fracture of the joint immediately upon cooling of the weld in the case when intermetallic compounds are present and cracks are formed in the joint. Chen and Kovacevic [7] pointed out that the maximum temperature in dissimilar FSW Al/steel is 631 °C on the steel side, which is drastically lower than that in fusion welding. Nevertheless, local melting of aluminum was observed in the weld, which can promote diffusion rate between the steel and aluminum substrates, thus IMCs tend to be formed in the Al/Fe system [7]. It has been reported that Fe-rich IMCs (*i.e.* FeAl) are not as detrimental to the mechanical performance of the joint as other Al-rich IMCs (*i.e.* Fe_4Al_{13}), since it has been argued that FeAl is more ductile [8]. Also, an IMCs layer will not drastically deteriorate weld strength when the thickness of which is less than 2 μm [9]. Hence, the mechanical properties of weld can be improved by altering the types, distribution and thickness of IMCs, through selecting welding parameters such as travel speed, and penetration depth.

During lap welding of dissimilar alloys, the key parameters to be considered include the tool geometry, rotation speed, and travel

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speed, as with all other FSW procedures. However, lap welding of dissimilar alloys also requires careful control of the tool pin length, and its penetration depth into the lower sheet material. For example, when aluminum or magnesium alloys are joined to steel, the pin penetration into the steel will rapidly wear away steel-based tools, and to avoid this one may maintain the pin above the sheet in order to promote diffusion bonding between the sheets [10]. That is, bonding could be promoted by an indirect diffusion joining mechanism while maintaining the tool pin around 0.05–0.1 mm above the surface of the lower steel sheet during Al5754/DP600 friction stir lap welding. This maintains the flat interface profile between the sheets, and results in fewer intermetallic compounds at the interface. This approach, however, precludes the contribution of mechanical interlocking between the sheets by deformation of the lower sheet into the upper sheet. It can also be difficult to maintain this small distance between the tool pin and the lower sheet steel surface. However, when a WC-based tool is used, the tool may penetrate into the steel sheet during joining without encountering severe wear. In prior work by Chen and Nakata [11], the influence of tool penetration was considered in Mg/Steel FSW joining, and it was shown that a thin interfacial reaction zone could be promoted when new layer of steel is exposed by the tool. Deformation of the steel sheet during tool penetration will also promote mechanical interlocking, which will contribute to joint strength [8]. However, this will also promote formation of intermetallic compounds when aluminum and steels alloys are joined, which may contain pre-existing cracks, have high hardness, and thus limit joint strength [10,12,13]. It should be noted that in comparison, other works involving diffusion bonding and adhesive bonding have always found that strengths are maximized when the thickness of reaction layer or intermetallic compound regions is minimized. For example, in the case of friction stir spot welding of aluminum to steel joining, it has been shown that bond strength deteriorates drastically once the reaction layer thickness exceeds 1.5 μm [14]. Considering this fine scale, it would appear that the FSW technique presents great potential in achieving the maximum theoretical strength between dissimilar joints, since the low temperatures and rapid speed of the process can be most effective in suppressing the growth of intermetallic compounds.

It is obvious that controlling the structure and phases at the interfacial region of dissimilar joints produced by FSW is very complex due to transient thermal cycles and short diffusion time. Since the influence of welding parameters on the structure and strength of the interfacial region remains unclear, the present work aims to determine the contributions of metallurgical bonding (via diffusion of aluminum and iron in the stir zone) and mechanical interlocking due to deformation of the lower steel sheet during FSW lap joining of AA5754 aluminum and DP600 steel sheets. The contributions of each will be assessed using a combination of microscopy, mechanical testing, and fractography.

2. Experimental procedure

The base materials examined consisted of 2.2 mm thick AA5754 aluminum and 2.5 mm thick DP600 dual phase steel, with the compositions shown in Table 1. A displacement controlled manual milling machine was utilized to fabricate FSW dissimilar joints, where a digital readout was used to control the displacement of the tool with a 0.005 mm precision. The tool material was a WC cermet with a 12 mm diameter shoulder, and a 5.1 mm diameter pin which had a length of 2.1 mm, and 3 flats, whose axis was tilted by 2.5° with respect to the vertical axis of the work piece and keeps constant during the process. The tool rotation speed during FSW was 1800 RPM, while travel speeds of 16 and 45 mm/min were compared, and penetration depth of the tool pin into the lower steel sheet increased up to 0.389 mm. The thermal cycle at the interface was also measured using K-type thermocouples placed directly at the edge of the pin boundary between the sheets, and temperatures were logged at a sample rate of 100 Hz.

Table 1
Nominal chemical composition of 5754 aluminum and DP600 steel (wt%).

AA5754	Mg	Si	Cr	Cu	Zn	Fe	Al	
	3.13	0.05	<0.01	0.23	<0.01	0.17	Bal.	
DP600	C	Si	Mn	Cr + Mo	Nb + Ti	Al	V	Fe
	0.17	0.80	2.20	1.00	0.15	2.00	0.20	Bal.

Optical microscopy was conducted on samples upon etching by 3% Nital to reveal the DP600 steel microstructure. The detail of AA5754 microstructure has been discussed by Haghshenas et al. [10]. Scanning electron microscope (SEM) characterization with energy dispersive X-ray (EDX) analysis was conducted on as-polished samples. All chemical compositions measured by EDX spectroscopy are reported as *wt%*. Wavelength dispersive spectroscopy was used to map the distribution of alloying elements, using a CAMECA SX100 electron probe microanalysis (EPMA) system.

The mechanical properties of the joints were measured during overlap shear testing, as well as microhardness testing. Overlap shear coupons were prepared with dimensions of 140 × 30 mm^2 with a 30 mm overlapped area and tensile tests were performed at a rate of 1 mm/min by using a Tinius Olsen (H10KT) Tensile Testing machine. All of the strength values were obtained by averaging the strengths of three individual specimens made at the same welding condition. Fracture morphologies of the failure specimens were examined by SEM, and X-ray diffraction (XRD) was used to investigate the phases present at the fracture surface.

3. Results and discussion

3.1. Macro-structural feature and SEM analysis

Analysis of specimens was limited to those which endured water-jet cutting for specimen preparation, and so superficially bonded joints were not considered in this study. Fig. 1a and b show the cross-sections of the welds produced using 45 and 16 mm/min at tool penetration depths of >0.17 mm. Increased tool penetration occurred in the sample produced at the welding speed of 16 mm/min, mainly due to the compliance of the FSW equipment. The lower travel speed produced greater heat and resulted in higher temperature at a constant rotational speed due to the increased processing time at a certain distance of the weld. Therefore, enhanced softening of the materials occurred which allowed the tool to penetrate 0.15 mm further into the DP600 steel sheet. Steel then moves up much more into the aluminum sheet and the height of hook reaches the maximum at 16 mm/min. Meanwhile, flash (material extruded upwards by the tool) formed at the surface of the weld due to the shoulder penetration into the aluminum sheet, especially, at the advancing side. Here the material flow is asymmetric with respect to the weld centerline.

As indicated in Fig. 1c, dynamic recrystallization occurs in the steel under the Al/Fe interface because the steel undergo heavy plastic deformation during FSW process, which exhibits equiaxed fine grains smaller than those in base metal (BM); this has been reported by Cho et al. [15] in the friction stir welded joint of high strength pipe line steels. Furthermore, the grain size increases from the Al/Fe interface to BM due to a decrease in deformation strain rates impose by the tool.

The SEM micrographs of the interfacial locations in the weld produced using 16 mm/min are shown in Fig. 2. The presence of