The Role of Joint Interface on Tensile-Shear Fracture Strength of Friction Stir Lap Diffusion Al-to-Steel Welds

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Abstract

Friction stir lap diffusion welding (FSLDW) of Al-to-steel experiments were conducted followed by mechanical testing and metallurgical examination of the welds to study the formation of microstructure at the interface region and its effect on fracture strength. It has been found that fracture strength was very sensitive to the distance (L_{dis}) between the bottom of the pin to the bottom steel plate. When L_{dis} was sufficiently small at 0.3 mm, interfacial diffusion and subsequent intermetallic formation was insured but the resulting intermetallic outbursts present along the interface represent the case of incomplete metallurgical joint established. As a result, joint strength is low. A slight pin penetration when $L_{dis} \approx$ -0.1 mm has been confirmed to provide a significant increase in joint strength where the interface region was a laminate of deformed steel and intermetallics. It has been found that at $L_{dis} \approx$ 0 mm, a joint was established with a continuous interfacial intermetallic layer and the weld test sample fractured in a ductile manner during in tensile-shear test, resulting in a considerable increase in fracture strength.

Introduction

In general, welding of Al aluminium alloy to steel, to Ti or to Cu is through diffusion at the interface and the subsequent formation of interfacial intermetallics. Defect free jointing by fusion welding of these alloy couples are generally difficult to be achieved. There have been a number of studies on friction stir lap diffusion welding of Al alloy to steel (FSLDW Al-to-steel) [1-5] but industrial application is yet to be widely reported. During FSLDW Al-to-steel where the Al alloy plate is normally placed on top, metallurgical bond is established also through diffusion and subsequent formation of interfacial intermetallic. Early investigation [1] on FSLDW Al-to-steel clearly established that the tool pin needs to slightly penetrate to steel for a continuous joint in the Al/steel interface. Pin penetration appears to have been accepted for promoting joint fracture strength (σ_f) [2,6].

For lap joints, tensile-shear test is commonly used and force per unit width is used as the unit. Early work on FSLDW Al-to-steel by Kimapong and Watanabe [3,4] showed that, under penetration condition, intermetallics form. Fe-Al intermetallics are however commonly viewed to adversely affect fracture strength (σ_f) [1,5,6]. Chen and Nakata's [7] reported σ_f equal to 163 N/mm for FSLDW Al-to-steel joints. This is a very low σ_f value and from their micrographs, a continuous bond cannot be confirmed. Coelho et al. [5] conducted FSLDW Al-to-steel experiments with tool pin having slightly penetrated to steel and continuous bonding at interface was established. Their σ_f values could not be evaluated as samples failed in FS nugget. More recently, Movahedi et al. [2] conducted FSLDW Al-to-steel experiments with pin sufficiently penetrated to steel over a wide range of speed conditions. Their maximum σ_f value reaches 304 N/mm for samples fractured along the joint interface.

In the above cited FSLDW studies, how the presence of intermetallics in the interfacial region actually affects σ_f, what should be the maximum attainable σ_f value, and what control can be made for constantly producing optimal joints are far from clear. In this work, FSLDW Al-to-steel experiments were conducted with various pin positions. Through post FSLDW testing and analysis, the effects of pin position dependent interfacial microstructure on fracture and on σ_f are established and a processing mean of controlling FSLDW for maximising σ_f can thus be suggested.

Experimental Procedures

FSLDW experiments were conducted using a milling machine. As indicated in Fig. 1, the top plate was 6 mm thick aluminium 6060 alloy and the bottom plate was 2 mm thick mild steel. The use of sufficiently thick top plate was to prevent fracturing in HAZ during mechanical testing. FS tools were made using tool steel (H13), in common with those cited studies [1,2,5,7]. The diameter of the concave shoulder was 18 mm, the threaded pin outside diameter was 6 mm. Tool tilt angle was 2.5°. Commonly used rotation speed values of 1000 and 1400 rpm and forward speed at 80 mm/min were used. Experiments were conducted using various pin positions in relation to bottom plate, expressed as L_{dis} in Fig. 1. To accertain L_{dis} position. the non-rotating tool was lowered till touching the surface of the top plate and the vertical control handle of the machine was assigned zero. Subsequently the rotating pin will be moved downwards for the required plunge depth. The movement of the vertical control handle can be controlled with an accuracy of ±0.05 mm.

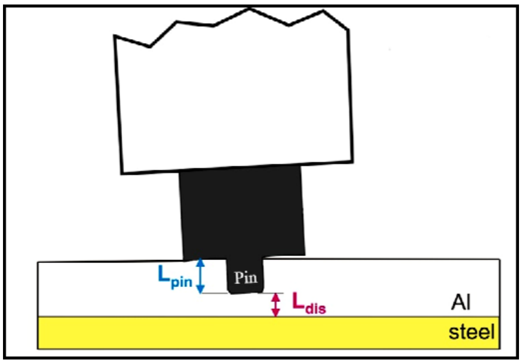


Fig. 1 Schematic illustration of friction stir lap diffusion welding.

Before each experiment, the steel plate was mechanically wire brushed to remove the surface oxide later. Experiments were first conducted using L_{dis} value equaling to 0.3 mm. This condition should result in a good interaction of the bottom Al flow zone and the bottom steel plate. In the second experiment, a L_{dis} value equaling to -0.1 mm was used. In this case, a slight penetration was assured, representing the suitable FSLDW condition, according to literature. In the third experiment, $L_{dis} \approx 0$ was aimed in order for the pin bottom just reaching the bottom plate without penetration. In this experiment, however, the tool was lowered slightly in the later stage, thus $L_{dis} \approx 0$ (Region 1) and $L_{dis} > 0$ (Region 2)) were obtained in one experiment.

After FSLDW experiments, samples were taken for tensile-shear testing and for metallography. Tensile-shear test samples and supporting pieces were 16 mm wide. Details of gripping a sample for testing, which is commonly used for testing lap joints, have been explained [9]. Samples were tested at a constant crosshead displacement rate of 3 mm/min using a 50 KN Tinus Olsen tensile machine. A 50 mm extensometer was attached to the sample during testing. Metallographic samples were mounted, polished and etched in 2% nital for examination.

Results and Discussion

The interface of the weld made using $L_{dis} \approx 0.3$ mm is shown by a SEM micrograph in Fig. 2. In this micrograph, steel is in focus and Al is not. A feature of the interface in this micrograph is the appearance of small outbursts clearly observed along the interface. Fe-Al intermetallic outbursts at the interface resulting from the early stage of interfacial intermetallic growth in Al-steel couples at high temperature is commonly observed [10]. Clearly, as shown in Fig. 2, the condition of this $L_{dis} \approx 0.3$ mm has not insured a continuous intermetallic layer, suggesting a possible non-continuous metallurgical bond.

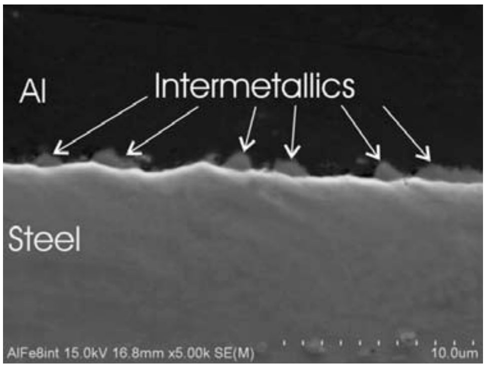


Fig. 2 SEM micrograph of interface in a weld made using $L_{dis} \approx 0.3$ mm.

The use of $L_{dis} \approx -0.1$ mm represents a slight pin penetration. This is shown in Fig. 3 and the penetrated width is significantly smaller than the pin diameter. The penetrated and thus the Al-to-steel interface region, as shown in Fig. 3, is a irregular laminate of Fe and Fe-Al intermetallic compounds, as has been suggested by the result of EDS mapping. The interface between the laminate region and Al is a continuous Fe-Al intermetallic layer. Thus, metallurgical bonding is complete in this penetrated region.

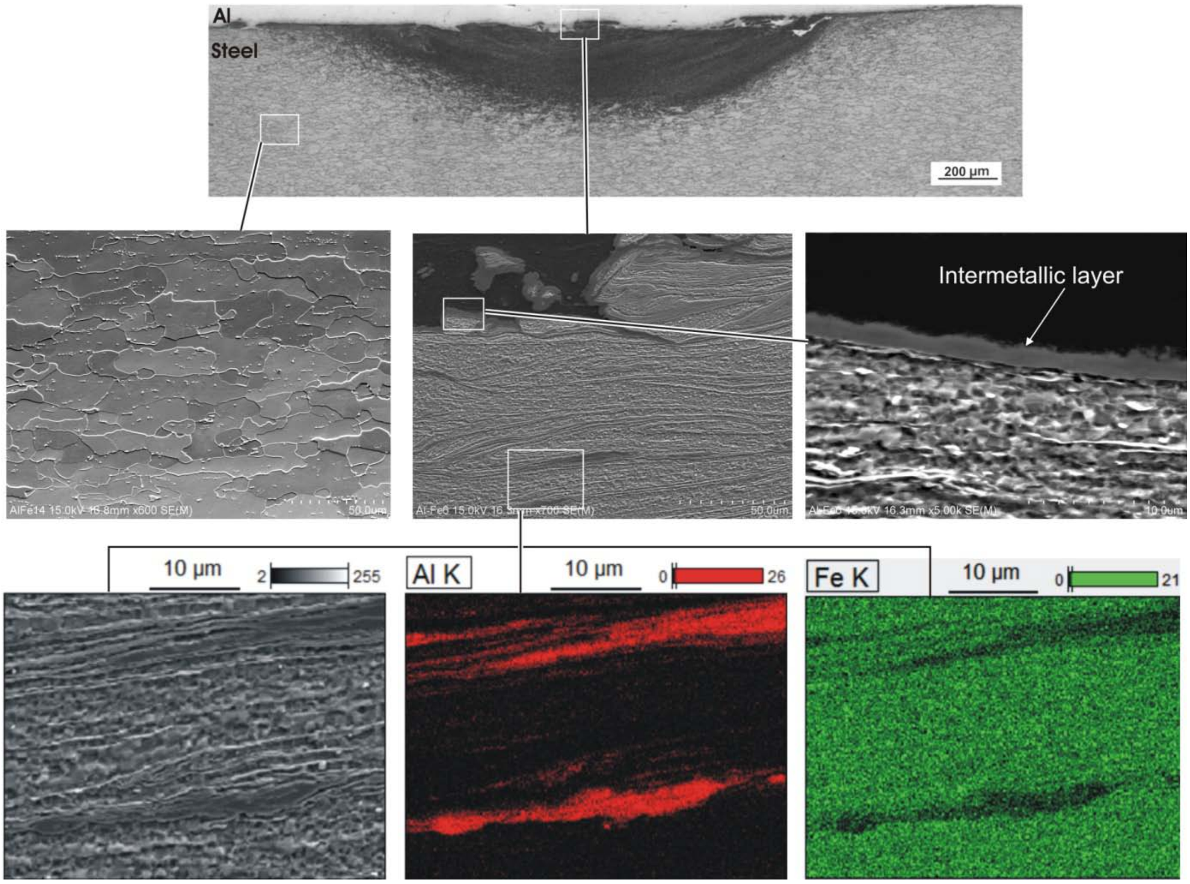


Fig. 3 Interface microstructures of a weld made using $L_{dis} \approx -0.1$ mm. Top: optical micrograph. Mid: SEM micrographs taken in locations indicated. Bottom: SEM micrograph and EDS maps taken in location as indicated.

For the case of $L_{dis} \approx 0.3$ mm, strength is low with an average value of a number tests being ~ 120 N/mm. The average σ_f value of welds made using $L_{dis} \approx -0.1$ mm is considerably higher, being ~ 300 N/mm. Fig. 4 show typical tensile-shear curves, one for weld made with $L_{dis} \approx -0.1$ mm and the other $L_{dis} \approx 0.3$ mm. The fracture energy, represented by the area under the curve, of the slightly penetrated weld is many times larger than that of the weld made without penetration. The σ_f value at ~ 300 N/mm is a high strength value considering that, as has been pointed out before, Movahedi et al. [2] conducted a series of FSLDW of Al-to-steel experiments with sufficient pin penetration and their maximum σ_f value was 304 N/mm.

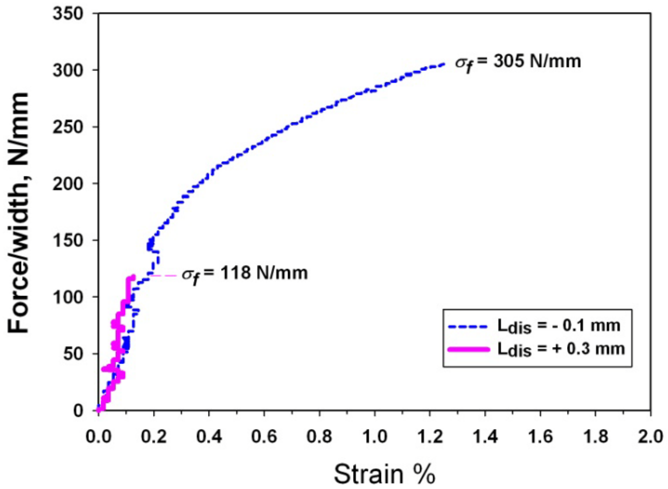


Fig. 4 Tensile-shear test curves for two samples, one taken from weld made using $L_{dis} \approx 0.3$ mm and the other using $L_{dis} = -0.1$ mm.

For the experiment that $L_{dis} \approx 0$ (Region 1) and $L_{dis} > 0$ (Region 2) were attempted, interface features are shown in Figs. 5 and 6, respectively. No penetration is suggested by the optical micrograph but a continued intermetallic layer with thickness of 1-2 μm in the bonded region is shown in the SEM micrograph in Fig. 5. It is expected that in the region of a steep temperature gradient, the interface slightly closer to the pin bottom may have resulted in higher interface temperatures. The effects of temperature on the intermetallic nucleation and growth are very strong [10]. In the present case, a slight increase in interface temperature may have resulted in a significant increase in the nucleation rate, thus forming a continued layer. In Region 2 ($L_{dis} > 0$), as shown in Fig. 6, significant pin penetrating took place. Comparing Fig. 6 to Fig. 3, the penetration should be significantly higher than 0.1 mm.

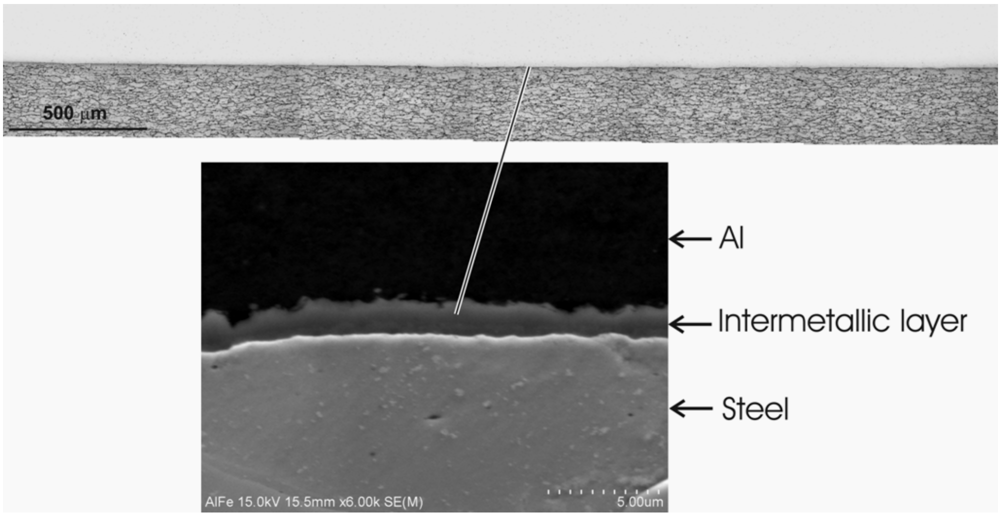


Fig. 5 Interface microstructures of a weld made using $L_{dis} \approx 0$. Top: optical micrograph and bottom: SEM micrograph taken in location indicated

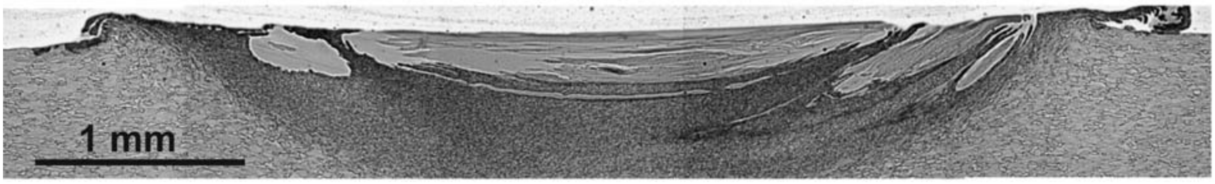


Fig. 6 Optical micrograph of interface of a weld made using L_{dis} > 0, showing a pin penetrating region significantly larger than the one shown in Fig. 3.

Tensile-shear test curves for samples taken in Regions 1 and 2 are presented in Fig. 7. For the Region 2 sample, σ_f = 299 N/mm is almost the same as those σ_f values of the weld made using a less penetration value in this work and is also almost the same as the maximum value (304 N/mm) of defects-free joints with sufficient penetration from Movahedi et al. [2]. This agreement suggests strongly that the attainable value for joint interface may not be significantly higher than 300 N/mm for the case of pin penetrating. For Region 1, as shown in Fig. 7, σ_f is high at 435 N/mm. The fracture energy of the Region 1 sample is also considerably higher than that of the Region 2 sample. A joint σ_f value of 435 N/mm is a high value. If a lap joint with this σ_f value was made using a top sheet 2 mm thick, the resulting σ_f value of the stir zone needs to be higher than 218 MPa to force the fracture in joint interface. A strength value of 218 MPa is close to the best attainable UTS values of as friction stir aluminium alloys.

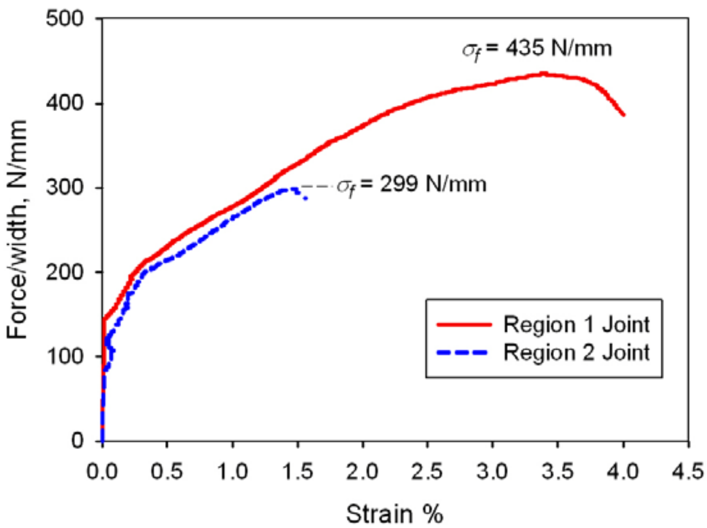
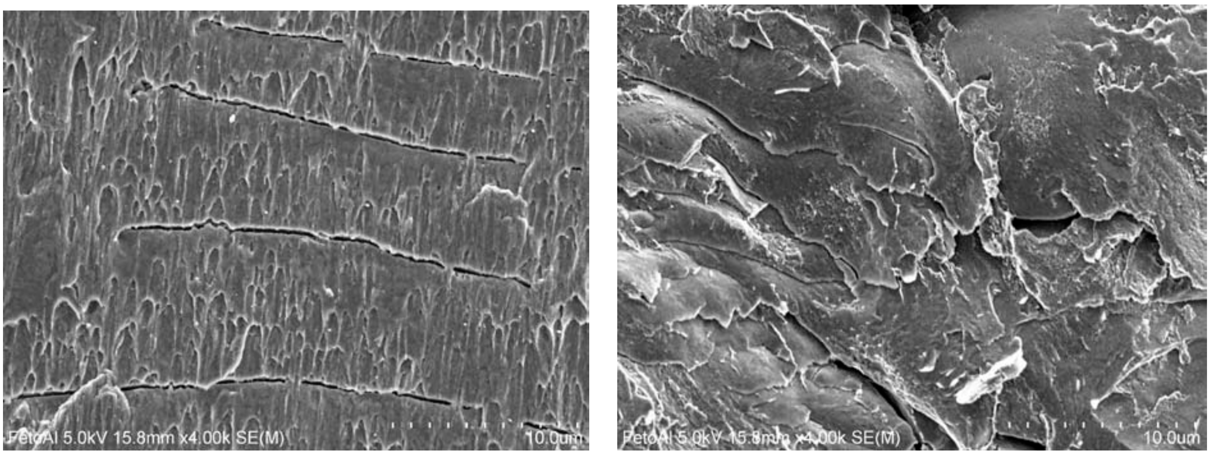


Fig. 7 Tensile-shear test curves for two samples taken in sampling Region 1 and Region 2, as indicated (note: in these curves data in the initial linear range are not presented).

Selected fractographs of tested samples are presented in Fig. 8. For Region 1, ductile fracture is dominant with plastic (shear) deformation preceding failure in aluminium adjacent to and on top of the intermetallic layer. This ductile deformation is consistent with the tensile-shear curve shown in Fig. 8 displaying high fracture strain and energy values. The cracks seen in Fig. 8a must be as thin as the thickness of the intermetallic layer and normal to the shear direction, thus contributing little to the shearing process. A significant portion of the fracture surface of Region 2 sample, as shown in Fig. 8b, displayed brittle failure feature. It is likely that cracking propagated along (parallel to) the thin intermetallic pieces/layers in the penetrated (laminate) region during testing. This brittle nature is also consistent with the tensile-shear curve in Fig. 7 showing lower fracture strain and energy values. The σ_f values from literature and from the present study obtained using various pin positioning values, together with the fracturing features observed, may have suggested that a force control mechanism of pin positioning can be effective for obtaining high tensile-shear strength welds.



(a) (b)

Fig. 8 Fracture surfaces of tensile-shear tested samples of (a) Region 1 displaying heavily deformed Al on top of the intermetallic layer and (b) Region 2 displaying brittle fracture of the intermetallics.

Conclusions

During friction stir lap diffusion welding (FSLDW) of aluminium to steel, the suggestion of a slight pin penetration to steel for promoting joint strength is valid as far as making sure a condition for a metallurgical bond to be embellished. This condition does not represent a joint condition for optimal joint strength (σ_f) value to be obtained. The present experiment has shown that FSLDW can be controlled that a thin intermetallic layer can form and thus metallurgical bonding is established, without the pin penetrating to steel. This joint produced by this non-penetrating experiment displayed a high σ_f value (435 N/mm) which was ~ 45% increase in σ_f in comparison to the σ_f value at ~ 300 N/mm commonly observed for the case of pin penetrating.

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