Friction Stir Lap Welding of Light Alloys

Z.W. CHEN* and S. YAZDANIAN*

*School of Engineering, AUT University, St Paul Street, Auckland 1010, New Zealand

E-mail : zhan.chen@aut.ac.nz

Friction stir welding (FSW) has been widely applied and studied intensively in recent times. The majority of FSW studies have been based on butt joint configuration. Joining with lap configuration is also widely used in rail, automotive and aerospace industries. Thus, various FS material flow related joint features and deformation and fracture behaviours of the joints under loading need to be better understood for FSLW to be more widely applied particularly for light weight structure applications. In this paper, features of hooking formed during FSLW of Al-to-Al and Mg-to-Mg will be quantified. These features are the results of two sequential material flows during FS which, as will be shown, are speeds dependent and alloy deformation behaviour dependent. Strength values of the welds will be presented and it has been found that hooking affects Al and Mg FSL welds very differently, due to the different modes of local plastic deformation. FSLW study has been extended to Al-to-Ti alloy, for which we will show that under a well controlled FSLW condition a thin and continuous interface intermetallic layer forms and this layer can bear a high shear load. As a result, the strength of the lap weld is very high.

Key Words : Hooking, Stress concentration, Fracture

1 INTRODUCTION

Friction stir welding (FSW) was invented in early 1990s [1] and is now applied widely for joining of aluminium alloys [2]. Although many aspects of FSW have been studied extensively, joint microstructures formed during friction stir lap welding (FSLW) and how the joints behave under loading need further understanding for a wider application of FSLW particularly in automotive and aerospace industries. Figure 1a illustrates FSLW during which a section of lapping surfaces of the top and bottom plates is stirred and mixed in the lower stir zone (SZ) thus forming a weld behind the tool. The joint features, depending on whether the jointing alloys are similar or dissimilar, are shown in Figure 1b and 1c. For the latter case, the lower stir zone is a mix of the two alloys for FSLW of dissimilar alloys, thus named mixed stir zone (MSZ).

Figure 1: Schematics of (a) FSLW and (b) SZ and a hook formed during FSLW of similar alloys and (c) SZ and MSZ formed during FSLW of dissimilar alloys.

During similar alloys FSLW, material deformation/flow affects the un-welded original lapping interface (referred to as *un-welded lap*) on both the retreating side and the advancing side. On advancing side of SZ and behind the tool, material flow can drive the material upward and thus a portion of the un-welded lap curves (hooks) up, forming a hook, as indicated in Figure 1b). The hook can be viewed as a crack that may orientate more favourably for crack growth under loading in service. In the studies of hooking and its effect on joint properties, a hook size (h) refers to the vertical distance of the hook [3-7]. Recently, we [8] have conducted a study of FSLW of aluminium to aluminium alloy (Al-to-Al) illustrating that, not only h , but the shape and the continuity of a hook can also influence the fracture strength significantly. FS heat results in softening in various regions of the weld zone. In our recent study [8], the relative roles of hooking and strength property distribution (affected by the thermal cycle during FSLW) affecting the weld strength have been explained for Al-to-Al welds. Furthermore, that referred study has also explained that stress distribution during the commonly used tensile-shear test of FSL welds is highly non-uniform.

Our study on FSLW had earlier also extended to magnesium to magnesium alloy (Mg-to-Mg) [9]. The study has suggested that although there is a similarity in the general trend of rotation speed (ω) and forward speed (v) affecting h for both Al-to-Al and Mg-to-Mg FSLW the effects of hooking on fracture strengths of the welds are significantly different. Hooking features rather than just h of Mg-to-Mg FSL welds had however not been discussed in our previous work and these features have thus far not been described in a sufficient detail in literature.

For lightweight construction, particularly in aerospace industry, welding of aluminium alloy to titanium alloy (Al-to-Ti) in lap

geometry is required [10], but fusion welding is highly challenging [11]. Melting and solidification problems can be avoided in FSLW and thus FSLW of Al-to-Ti can potentially be applied. Early work by Chen and Nakata [12] has demonstrated the maximum failure load equal to 9,390 N for a 20 mm wide Al-to-Ti FSL weld. This is equivalent to 156 MPa if a top 3 mm plate is considered and is a reasonably good joint strength value. They also showed that when the tool pin penetrated to the bottom plate thus forming a MSZ, joint strength reduced. They showed voids in the MSZ and suggested that this void defect assisted cracking during subsequent mechanical testing. However, how the different modes of fracture due to the large difference in microstructures in the interface region was not explored further. In the more recent studies on FSLW of Al-to-Ti [13,14], values of joint strength are significantly lower.

In the present work of FSLW of light alloys, further characterising both Al-to-Al and Mg-to-Mg welds are made to illustrate the different hook forming behaviours during FSLW. Furthermore, in this study, the mechanical behaviours during tensile-shear testing due to the differences in local deformation for the two different alloy couples affecting their fracture strengths are explained. For Al-to-Ti, joint strength affected by the microstructures formed in the interface region during FSLW is evaluated.

2 EXPERIMENTAL PROCEDURES

FSLW experiments were conducted using a milling machine. Workpiece materials were 3 mm A6060-T5 aluminium alloy plates for Al-to-Al and 2.5 mm AZ31B-H24 magnesium alloy plates for Mg-to-Mg FSLW. For Al-to-Ti FSLW, using 2.5 thick Ti-6Al-4V alloy plates, the top plate was 6 mm thick A6060-T5 to force fracturing in the interface region in order to study the interface region of the joint. Both top and bottom plates were 200 mm long and 100 mm wide. Tools were made using H13 tool steel and the left-hand threads of the pins were made with a 1 mm pitch and a 0.6 mm actual depth. The diameter of the concave shoulder was 18 mm for Al-to-Al and Mg-to-Mg and 25 mm for Al-to-Ti and the pin outside diameter was 6 mm. A tool tilt angle (θ) of 2.5° was used. In the present experiments, forward speed (v) ranged from 20 to 630 mm/min and rotation speed (ω) ranged from 500 to 2000 rpm. Directions of v and ω are as indicated in Figure 1a. For the work reported here, the bottom of the tool pin penetrated to the bottom plate ~ 1 mm for Al-to-Al and Mg-to-Mg. For Al-to-Ti, penetration was carefully adjusted aided by the monitoring the downforce [15] so that the pin just touched or slightly penetrated was possible.

Tensile-shear testing of lap welds has been the major method used for evaluating strength of FSL welds in literature and was adopted in this study. Test samples, 16 mm wide, perpendicular to the welding direction were machined from the welded plates. Figure 2 illustrates a sample positioned with supporting pieces. Tests were conducted at a constant crosshead displacement rate of 3 mm/min using a 50 KN Tinius Olsen tensile machine. The strength of a lap sample cannot be expressed using the normal

Figure 2: Schematic illustration of tensile-shear testing.

load/area expression, as the stress distribution along the joint area is highly uneven. Instead, maximum load in a test divided by the sample width, F_m/w_s , is taken to indicate how strong the sample is. For microstructure observation using optical microscope and SEM/EBSD, the welds were cross-sectioned, mounted and polished following the normal metallographic procedure.

3 RESULTS AND DISCUSSION

3.1 Al-to-Al and Mg-to-Mg welds

In Figure 3a, the SZ has been outlined and the hook outside, but very close to, SZ is shown. Material flow in the lower part of SZ during FS as indicated in the figure pushed up a small portion of the un-welded lap, thus forming the hook. These features are common in FSL welds [4-6]. In Figure 3b and 3c, microfeatures of the hook are further shown. The shape (elongated) and orientation of grains in the area including the edge of SZ and thermomechanical affected zone (TMAZ) are clearly different from those in heat affected zone (HAZ) which are largely equiaxed with a different texture. Thus, not only there is an upward flow induced by the pin, there is also a sideward flow (deformation) in the mid-upper region caused by the tool shoulder and the grains were deformed and elongated.

Figure 3: Cross sectional views of A6060 weld made using $\omega = 1,000$ rpm and $v = 224$ mm/min, (a) macro/micrographs displaying a hook with SZ outlined and FS flow direction indicated, (b) and (c) EBSD pattern quality and orientation maps (red 001, green 101, blue 111), respectively, of the hook region.

The sequential flows can be summarized in Figure 4. The pin induced bottom flow first lifts the un-welded lap in TMAZ upward. Later, in the mid-upper region of SZ/TMAZ, the rotating shoulder forges the material not only forward but also sideward due to the material in the upper region being sheared from retreating side to advancing side behind the pin. Thus the whole SZ appears generally in a bell shape, as outlined in Figure 3a, in Al-to-Al welds. The upper portion of a hook is thus also forged and sheared sideward and away from the pin. The size and orientation, expressed as angle γ in Figure 4, of a hook depend on the intensities of the two flows.

Two measured h values of hooks shown in Figure 5 are almost equal, but they are very different in both the shape and "quality". On shape, $\gamma = 46^\circ$ in Hook A and $\gamma = 70^\circ$ in Hook B, meaning a stronger sideward flow (more deformation sideward) for Hook B. A larger amount of deformation (strain) can result in the lapping

Figure 4: Schematic illustration of (a) pin and (b) shoulder related upward flow and sideward flow, respectively.

Figure 5: Micrographs of two hooks of A6060 welds with different hook angles (γ) and local hook discontinuities as pointed to by arrows.

interface locally closed. Thus, discontinuity is very severe in Hook B. A strong sideward flow should result in part of the section towards the end having closed completely. Thus, as already observed [8], part of the original lapping interface has disappeared, meaning that if a hook was unfolded it would not reach where the pin was.

On features of hooking in Mg-to-Mg welds, an example of high h hooking, shown in Figure 6a and 6b, is examined first. The pin induced upward flow very effectively lifted the un-welded lap a long distance up. But, the sideward flow caused by the shoulder, in comparison to the one during Al alloy FSLW, must be very weak during Mg alloy FSLW, even though ω was high. This weak sideward flow (plastic deformation) has resulted in $\gamma \ll 0$, as is clear in Figure 6b. The use of a low ω value and higher v value, as expected, resulted in a low upward flow and thus a low h value at 0.28 mm in Figure 6c compared to $h = 1.34$ mm in Figure 6b. For the low ω value weld, γ value is slightly below zero suggesting no

Figure 6: Cross sectional views of AZ31B welds made using (a) and (b) $\omega = 1,000$ rpm and $v = 112$ mm/min displaying a large hook, and (c) $\omega = 500$ rpm and $v = 224$ mm/min displaying a small hook.

sideward flow. The lack of sideward flow is consistent with little hook discontinuity in Mg-to-Mg welds. The reason why sideward flow is very low during Mg alloy FSLW is at present not very clear.

Values of F_m/w_s for Al-to-Al and Mg-to-Mg FSL welds [8,9] are replotted as a function of h in Figure 7. For Al-to-Al welds, as a comparison, the range of F_m/w_s values of FS bead-on-plate samples, which should represent defect-free butt welds, is provided. In other words, data provided in Figure 7 also serve as a comparison of strength values for both butt welds (defects free) and lap welds. Data in Figure 7a has shown clearly that as $h \rightarrow 0$, F_m/w_s of the lap welds is the same as that of a defect-free butt weld. Furthermore, as is also clear in Figure 7a for the lap welds, $d(F_m/w_s)/dh$ is small meaning that F_m/w_s is affected by h only slightly, for h up to ~ 0.9 mm. It should be noted that the top plate is only 3 mm and a hook size of 0.9 mm is not small. This implies that h value may not always have a dominant effect. As indicated in Figure 7a, when h is small the effect of HAZ dominates. For Mg-to-Mg welds, Figure 7b shows that as $h \rightarrow 0$, $F_m/w_s \approx 255$ N/mm. Strength values for butt AZ31B-H24 FS welds are about 200 MPa [16] and for a 2.5 mm thickness we should expect the strength equivalent ($F_m/w_s \approx 500$ N/mm. Then, F_m/w_s (lap) ≈ 255 N/mm $\ll F_m/w_s$ (butt) ≈ 500 N/mm.

It should be noted, a weld made using FSLW totally differs from a butt weld when it is subject to loading, as there will always be a un-weld lap. Even when $h = 0$, the un-weld lap acts as a pre-crack and there is a high stress concentration around the crack (lap) tip during testing. This difference is, however, not apparent when examining the data in Figure 7a for Al-to-Al welds. As shown in the figure, $F_m/w_{s(lap)} = F_m/w_{s(butt)}$ as $h \rightarrow 0$. This is due to local deformation and bending of the sample around the joint location during testing and the sample effectively reorients and stress concentration diminishes as the test progresses. Local deformation to final fracture then can preferentially locate in the HAZ. Thus, $F_m/w_{s(lap)} = F_m/w_{s(butt)}$ (as $h \rightarrow 0$). In Figure 8a, Al-to-Al welds are shown to locally deformed and bent extensively before final fracture.

Figure 7: Strength values plotted as a function of hook size for (a) A6060 welds and (b) AZ31B welds.

Figure 8: Tensile-shear tested samples of (a) A6060 welds and (b) AZ31B welds.

On the other hand, all Mg lap weld samples fractured in hook location with little bending, as shown in Figure 8b. Little local deformation/bending means the high stress concentration unrelaxed. The effective stress in the hook region should be at least 3 times of the applied stress [8]. This is thus the reason why F_m/w_s (lap) $\ll F_m/w_s$ (butt). Microstructures of an AZ31B tested sample are shown in Figure 9, featuring the dynamically recrystallized grains in SZ as the result of thermomechanical processing during FS. Adjacent to the fracture surface, the general shapes of grains are not seen altered extensively meaning a low level of deformation by slip. Dense twins are observed, suggesting deformation by twinning but the total amount of deformation must be quite low before fracturing. These observations are in common with the

Figure 9: Microstructures of a low h value AZ31B tested sample, (a) mid stir zone and (b) region of fracture.

known deformation behaviours of this alloy, particularly the feature of little necking during tensile testing.

3.2 Al-to-Ti welds

Tensile-shear curves for Al-to-Ti samples of the weld made using $v = 20$ mm/mm are shown in Figure 10. One is for a sample of the weld made with pin toughening the bottom plate (Region 1 sample) and the other for the condition of the tool having penetrated the bottom plate. As has been explained, the pin positioning was assisted not only by vertically adjusting the pin but also by monitoring the down force. As illustrated in Figure 10, strength of the sample made with zero pin penetration (but touching) is considerably higher. Similar results of considerable difference in strength values from a weld made using $v = 80$ mm/min (not shown) have also been obtained.

As expected, Region 2 sample contained a MSZ. $F_m/w_s = 340$ N/mm is close to the value of 375 N/mm obtained by Chen and Nakata [12] for a weld of pin penetration and thus containing a MSZ. As shown in Figure 10, $(F_m/w_s)_{\text{Region1}} / (F_m/w_s)_{\text{Region2}} > 2$. In comparison, from data of Chen and Nakata, $(F_m/w_s)_{Dp \rightarrow 0} / (F_m/w_s)_{Dp > 0} \approx 1.3$ and their F_m/w_s value for zero penetration is 470 N/mm. As has been shown in Figure 7a for Al-to-Al welds, for small h , $F_m/w_s(\text{lap}) \approx F_m/w_s(\text{butt})$, the maximum value of which from a group of 3 mm bead-on-plate sample was actually ~ 150 MPa. If a value of 732 N/mm F_m/w_s is to apply to a 3 mm thick and 16 mm wide FS butt weld sample, the stress value is 244 MPa. Hence, the strength value of the Al-to-Ti sample equal to 732 N/mm may be considered, comparatively, a very high value.

Region 1 sample fractured in α -Al near the interface in a highly ductile manner, as is clear in Figure 11a. This suggests that the fracture toughness of the interface layer must be sufficiently high and does not crack during testing. Fracture did not proceed by

Figure 10: Tensile-shear curves of two samples of an Al-to-Ti FSL weld (strain within sample gauge length). Region 1 is for zero pin penetration and Region 2 for pin penetration.

Figure 11: SEM fractographs of a tensile-shear tested sample of an Al-to-Ti weld made with (a) zero pin penetration and (b) pin penetrating.

deformation and crack growth in α -Al in the Region 2 sample. Instead, cracks propagated inside the MSZ, likely along the irregular layers of intermetallics mixed in the zone, as shown in Figure 11b. This fracture appearance is similar to fracturing along the irregular Al-Fe intermetallic layers inside the MSZ as has also been detailed [15].

The above result indicates that in order for a high joint strength to be obtained, the pin needs precisely positioned. In Chen and Nakata's experiment [15], as they also stated, the pin did not touch the bottom plate. As we have demonstrated [18], for Al-to-steel FSLW, a negative but close to zero penetration can result in local intermetallic formation thus bonding Al-to-steel locally. It can be suggested that in Chen and Nakata's experiment, the width (normal to the weld direction) of joining by a metallurgical bond may be small in comparison to the diameter of the pin. On the other hand, as we have explained, the pin did touch the bottom plate in our experiment. The width of bonding of our sample is thus high. This may explain that the F_m/w_s value of our sample is also considerably higher.

CONCLUSIONS

During friction stir lap welding (FSLW) of Al-to-Al, the size (h), orientation (γ) and continuity of a hook formed are FS material flow dependent. While the pin related flow is fundamental for hooking to form, γ and continuity are affected by shoulder related flow. For $h \rightarrow 0$, strength (F_m/w_s) of a weld is largely the same as the strength of a bead-on-plate FS sample. In both cases, FS softening dominates and stress concentration (σ_c) does not affect F_m/w_s of lap samples significantly due to local bending to reduce considerably σ_c . Thinning effect on F_m/w_s due to hooking can be masked by the effect of softening when h is not very high. During FSLW of Mg-to-Mg, shoulder related flow is very weak which results in little reduction in h , little hook reorientation and little reduction in hook continuity. For Mg-to-Mg welds, F_m/w_s (lap) $\ll$ F_m/w_s (butt), due to σ_c effect. Strength of Al-to-Ti joints made by FSLW can be very high when positioning of pin is well controlled during FSLW to result in a fully developed weld without a MSZ. Under this condition, the interface layer formed can be subjected to a high shear load without fracture and the adjacent α -Al deforms and fractures instead. As a result, the strength of the Al-to-Ti lap weld is very high.

References

- [1] Thomas W., et. al., G B Patent Application (1991) No. 9125978.8.
- [2] S.W. Kallee, S.W., in *Friction Stir Welding – from basics to application*, ed. Lohwasser, D., Chen, Z., (Cambridge: Woodhead Publishing, 2010), 118-163.
- [3] Ericsson, M., Jin, L. Sandström, R., *Int. J. Fatigue*, **29**, 57-68 (2007).
- [4] Buffa, G., et. al., A., *Mater. Sci. & Eng. A*, **519**, 19-26 (2009).
- [5] Yadava, M.K., Mishra, R.S., Chen, Y.L., Carlson, B., Grant, G.J., *Sci. & Tech. Weld. & Join.*, **15**, 70-75 (2010).
- [6] Dubourg, L., Merati A., Jahazi, M., *Mater. & Des.*, **31**, 3324-3330 (2010).
- [7] Cao, X., Jahazi, M., *Mater. & Des.*, **32**, 1-11 (2011).
- [8] Yazdani, S., Chen, Z.W., Littlefair, G., *J. Mater. Sci.*, **47**, 1251-1261 (2012).
- [9] Chen, Z.W., Yazdani, S., Littlefair, G., *Adv. Mater. Res.*, **275**, 73-76 (2011).
- [10] Moller, F., Grden, M., Thomy, C., Vollertsen, *Phy. Procedia*, **12**, 215-223 (2011).
- [11] Lv, S.X., et. al., *Sci. & Tech. Weld. & Join.*, **17**, 519-524 (2012).
- [12] Chen, Y.C., Nakata, K., *Mater. & Des.*, **30**, 469-474 (2009).
- [13] Wei, Y., Li, J., Xiong, J., Huang, F., Zhang, F., Razam, S.H., *Mater. Charact.*, **71**, 1-5 (2012).
- [14] Chen, Y., Ni, Q., Li-ming, K.E., *Trans. Nonferrous Metals Soc. China*, **22**, 299-304 (2012).
- [15] Chen, Z.W., Yazdani, S., Littlefair, G., *J. Mater. Sci.*, **48**, 2624-2634 (2013).
- [16] Chowdhury, S.M. et. al., *Mater. Sci. & Eng. A*, **527**, 6064-6075 (2010).