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Aluminum Friction Stir Weldbonding

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Abstract

The push towards lightweight efficient structural design has led to an increasing interest in joining technologies for aluminum alloys. Although the use of these alloys has previously been restrained by production difficulties associated with their poor welding properties, friction stir welding and adhesive bonding allowed for a larger flexibility in lightweight structural design. In this work a combined joining process of this welding technique with adhesive bonding (friction stir weldbonding) is presented. Quasi-static mechanical properties, fatigue behavior and other properties of the friction stir weldbonding joints were assessed and compared with adhesive only and welded only joints.

Friction stir welding (FSW) is a revolutionary joining method that allowed welding of previously unweldable alloys with excellent characteristics, and has an enormous potential for application in a large array of industries. Even though friction stir welding presents several advantages over other welding techniques when regarding joining of aluminum alloys, it also presents its share of challenges. For example, in the case of overlap configuration joints, which are very common in structural design, the presence of a hook defect reduces the static and fatigue strength as this defect acts like crack initiation point. In certain alloys the question of chemical corrosion is also a factor requiring good sealant measures to avoid degradation.

The combination of FSW with adhesive bonding (AB), forming friction stir weldbonding may present itself as a solution for these concerns. The development of this new joining technology aims at incorporating properties and characteristics of both joining technologies, as well as improving damage tolerance. FSW is able to produce consistent joints with high static strength, while the adhesive will not only allow improved vibration damping and fatigue strength but may also serve double duty as a sealant, isolating the weld from the environment. Damage tolerance is improved, by having to failure mechanisms, cohesive rupture in the adhesive and ductile and shear failure in the aluminum.

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Keywords: friction stir welding, adhesive bonding

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1. Introduction

In this work the development of hybrid friction stir welding and adhesive bonding single lap joints is addressed.

Nomenclature

AB	adhesive bonding
FSW	friction stir welding
TWI	the welding institute

A combination of regulatory requirements [1] and market demand [2, 3] have pushed for continuous improvements in energy efficiency and performance in transport solutions. Weight reduction through the use of new lightweight alloys and new structural designs is detrimental to these goals [3]. In order to implement lighter materials and innovative structural designs new manufacturing processes are required.

One such technology is friction stir welding (FSW), a joining process developed at TWI [4] with disruptive potential. This disruptive potential arises from the fact that FSW is a solid state joining process, which means the materials are joined at temperatures below melting point. As a result of this, previously unweldable materials are capable of being joined by this technique with good mechanical properties, low distortions, good surface finish and high automation potential. Vast research was and still is performed on the topic of FSW, but along with this research many cases of industrial application of the technique may be found, as is the case presented in [5].

Another technology, which although has a longer history, has received much development and research interest in the recent past for its lightweighting potential is adhesive bonding (AB). Recent research in this field has focus on adhesive properties and applications at high and low temperatures [6], fracture characterization [7], development and validation of numeric simulation tools [8, 9], self-healing and thermally expandable particles in adhesive joints [10], application cases [11, 12] as well as many other topics.

Damage tolerance principles have favored hybrid joining technologies which include two or more different joining techniques. AB has been a recurrently employed technique in these hybrid joining methods due to its manufacturing advantages, favorable joint properties as well as its flexibility. The practical application potential of hybrid joining technologies has allured many researchers and as such several studies on the matter may be found in the literature.

Moroni et al. in [13] studied hybrid single lap joints using resistance spot welding, riveting, clinching and self-piercing riveting in conjunction with adhesive bonding. The joints were tested for static strength, stiffness and energy absorption and were compared to only bonded and only mechanically joined or welded joints. The conclusions taken from this experimental study were that, weld-bonded joints presented generally an increased strength stiffness and energy absorption when compared with spot welded joints, and that the contribution of the adhesive bonding was more evident in hybrid-fastened joints than in weld-bonded joints. This study also shown that based on the application requirements it was possible to "tailor" the joint with these hybrid joining techniques.

Since FSW is a relatively more recent technology than riveting, spot or laser welding for example, studies regarding hybrid FSW-bonded joints are less commonly found in the literature. Chowdhury et al. in [14] produced and tested friction stir spot welded bonded dissimilar joints of magnesium and aluminum. The produced joints micrography, hardness, lap shear strength, and fatigue strength were evaluated and compared to reference only friction stir spot welded joint. The hybrid bonded joints shown improvement in lap shear strength and failure energy regarding the only friction stir spot welded joints. Fatigue life was improved as well when using adhesive in the friction stir spot welded. Even though scientific publications regarding the FSW+AB hybrids are scarce patent fillings may be found, such as [15]. Beyond FSW+AB hybrid joints, FSW has also been combined with other welding techniques or heat sources in or to create hybrid techniques, e.g. FSW and laser [16].

In this study a manufacturing process for hybrid FSW and AB aluminum lap joints was developed. Static strength and distortion levels of the manufactured joints were assessed and compared to FSW only and AB only joints, for benchmarking purposes.

2. Experimental

2.1. Materials and Friction Stir Welding Conditions

The material used in this study was 2 mm thick AA6082 in T6 condition. The chemical composition and mechanical properties of the aluminum alloy employed in this study are presented in Table 1 and Table 2 respectively.

Table 1 Chemical composition of AA6082-T6 (% mass) [17]

Manganese (Mn)	**Iron (Fe)**	**Magnesium (Mg)**	**Silicon (Si)**	**Copper (Cu)**	**Zinc (Zn)**	**Titanium (Ti)**	**Chromium (Cr)**	**Others (Total)**	**Aluminium (Al)**
0 - 1.00	0.0 - 0.50	0.60 - 1.20	0.70 - 1.30	0.0 - 0.10	0.0 - 0.20	0.0 - 0.10	0.0 - 0.2	0.0 - 0.1	Balance

Table 2 Mechanical properties of AA6082-T6 [17]

Material	**Young Modulus [GPa]**	**Yield strength [MPa]**	**Ultimate tensile strength [MPa]**	**Elongation [%]**
AA6082-T6	70	>260	>310	7

The structural adhesive employed in this study was the commercially available Araldite 420 from Hunstman®. Prior to bonding, surfaces were sandblasted and degreased with acetone. Furthermore in the case of AB, a joint was produced using phosphoric acid anodized surfaces (reference AB-Anod), as described in [18]. The adhesive bonded lap joint with sandblasted and acetone degreased surfaces has the reference AB-SB.

The friction stir welds were produced in a ESAB LEGIO™ 3UL numeric control machine. Welding was performed under vertical downward force control. The FSW parameters used in this study were selected from a combination of trial and error and previous experience in manufacturing FSW lap joints. Along with the set of FSW process parameters listed in Table 3, the vertical force was varied between 400 kgf and 450 kgf for single pass welds. In the case of double pass welds the vertical force was either 450kgf and 400kgf for first and second pass respectively or 400kgf and 320kgf. The same process parameters were used for both hybrid FSW+AB joints and FSW only joints. Double pass welds were performed in order to guarantee that the advancing side was facing inwards in the joint since in FSW lap joints a critical hook defect appears along the advancing side of the joint, reducing the joint strength.

Table 3 Fixed FSW parameters

FSW Control	Vertical Force
Rotation Direction	CW
Plunge Speed	0.1 mm/s
Dwell time	5 s
Tilt angle	0º
Welding speed	200 mm/min
Rotational speed	1000 rpm
Probe length	2.8 mm

In the hybrid joints, beyond the variation in vertical force the use of two purpose made channels for the adhesive was also tested versus a continuous layer of adhesive in the interface between the two aluminium plates. The channels had 10 mm width and 0.2mm depth and were positioned 34 mm apart from each other. The welding procedure in these joints occurred within 15 minutes of the adhesive bonding procedure (adhesive not cured) and then the adhesive continued curing at room temperature.

A patented modular concept of FSW tool composed by three main components; body, shoulder and probe, was used to produce the joints in this study. A threaded cylindrical shaped probe with 5 mm diameter was used in this FSW tool (see Figure 1). The probe was mounted on a 16 mm diameter shoulder. Specimens restraining during welding was done at a distance of 10 mm towards the weld line in both sides of the weld.

Figure 1 FSW tool used.

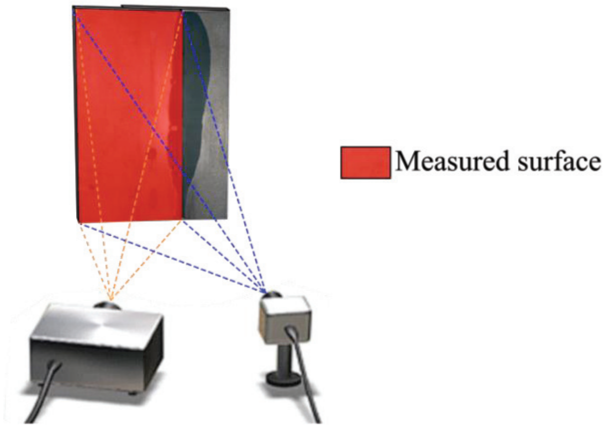
The resulting experiment matrix is presented in Table 4.

Table 4 Experiment matrix

		1-FSW-1	1-FSW-2	2-FSW-1	2-FSW-2	1-Hyb-1	1-Hyb-2	1-Hyb-3	1-Hyb-4	2-Hyb-1	2-Hyb-2
Vertical Load (kgf)	1st pass	400	450	400	450	400	450	400	450	400	450
	2nd pass			320	400					320	400
Channel for Adhesive		-	-	-	-	Yes	Yes	No	No	Yes	Yes

2.2. Distortion measurement

Distortions were compared between joints using DAVID-3D SCANNER with a structured light array to acquire the 3D shape of the bottom plate,



as shown in

Figure 2, bottom surface of the lap joints. Since distortion is a complex physics entity to compare, a MATLAB® code was developed which interpolates the measured points in the surface to a regular grid, calculates the centroid and middle plane of the obtained surface, and two parallel planes to this middle plane passing through the two points furthest distanced to the middle plane (e.g. Figure 3). The distance between the two planes is therefore the value of distortion compared. The obtained distortion measurements are shown in Figure 4.

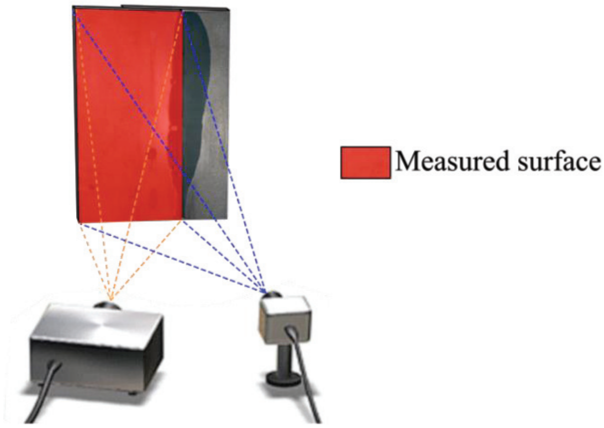


Figure 2 Scheme of the measured surface using David-3D scanner.

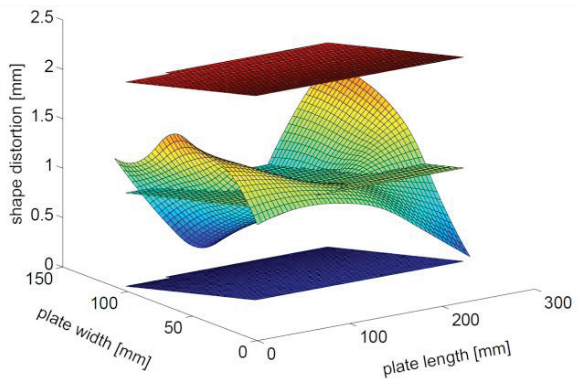


Figure 3 1-Hyb-2 distortion measurement using the indicated procedure (off plane direction not to scale).

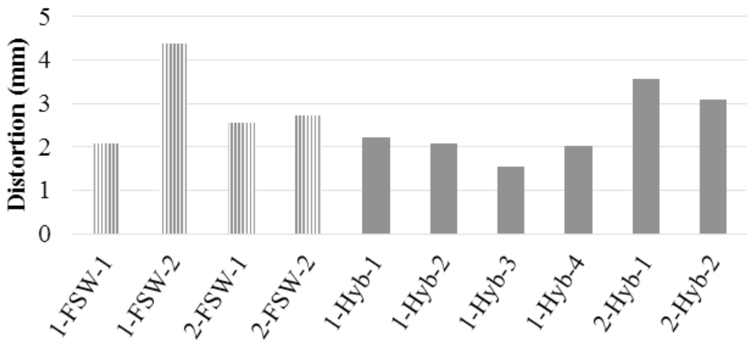


Figure 4 Distortion measurements.

In the case of FSW joints it is possible to notice that increasing the vertical load force (e.g. from 1-FSW-1 to 1-FSW-2) increases the distortion level, which is justified by the higher heat input resultant of friction between tool and workpiece, although in double pass welding this increase is less significant. For the lowest vertical force values, double pass FSW welds showed an increase in distortion level regarding single pass welds. Single pass hybrid joints present relatively similar distortion levels and similar to the single pass FSW weld with the lowest vertical force level. Only the single pass hybrid joint produced with the lowest vertical force level and with a continuous adhesive layer (1-Hyb-3) showed a reduction in distortion levels, which is possibly due to the fact that the adhesive is in a non-cured state when the FSW procedure is performed and possibly serves as a “damper” for this vertical force. Also a more even distribution of heat to the lower plate, since the adhesive is less thermally conductive than aluminum may justify this reduction in distortion. In the case of hybrid joints produced with adhesive within pre made channels, distortion levels are either constant or reduce with increased vertical force while joints manufactured with a continuous layer of adhesive show an increase in distortion levels with increase vertical force.

When comparing double pass FSW only welds and double pass hybrid joints with adhesive in pre made channels, distortion levels are higher in hybrid joints, possibly because the adhesive serves as an isolation layer and the temperature in the upper plate is kept higher throughout the FSW process, due to the heat input from both weld passes and lack of heat dissipation.

2.3. Lap shear strength tests

Lap shear strength of the produced joints was assessed through monotonic testing using specimens based on ASTM D1002-01 standard. Tests were performed at 1 mm/min speed.

Figure 5 shows the maximum loads achieved during testing for the different joints.

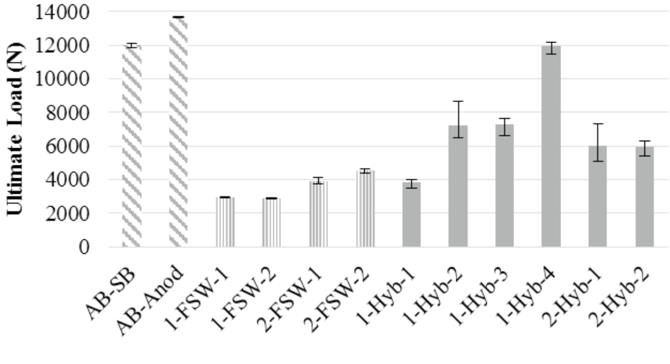


Figure 5 Maximum single lap shear load.

The load versus displacement curves for the joints with the highest ultimate loads are presented in Figure 6.

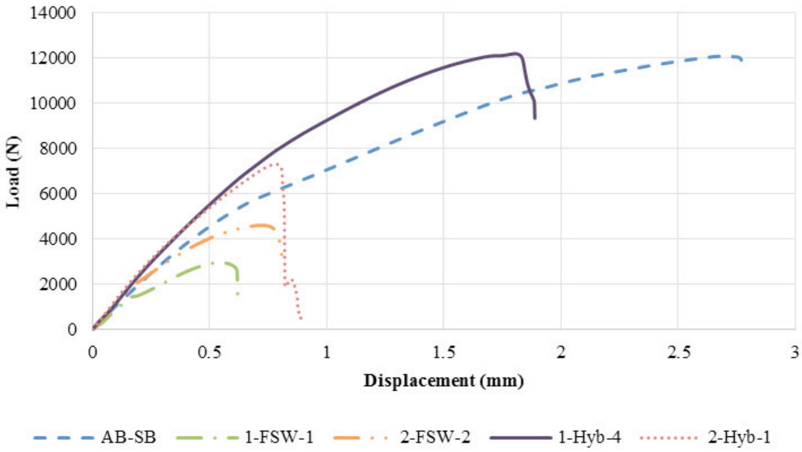


Figure 6 Load vs. displacement curves.

When comparing the load versus displacement curves it can be observed that adhesive joints not only present higher ultimate loads than FSW joints, they also show higher displacement upon failure, meaning that they absorb more energy. The best hybrid joint (1-Hyb-4) presents a similar ultimate load than the adhesive joint, but with lower displacement upon failure.

Figure 7 compares adhesive joints with two different surface treatments, sandblasting (AB-SB) and anodization (AB-Anod).

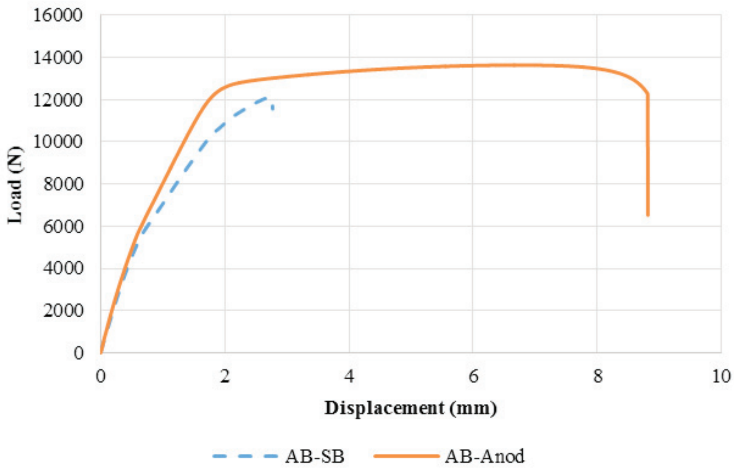


Figure 7 Load vs. displacement curves of adhesives joints with different surface treatments.

Anodization has shown to be a more suitable surface treatment for aluminum joints (adhesive and hybrid), since Figure 7 shows the anodized adhesive joints present higher ultimate load and displacement upon failure. This is also justified when analyzing the failure surfaces of all joints, as all sandblasted adhesive and hybrid joints shown either an adhesive or mixed adhesive-cohesive failure, and the anodized adhesive joints shown cohesive failure with plastic deformation of the substrate, due to the relatively high overlap length.

3. Conclusions

A successful procedure to manufacture hybrid FSW and adhesive bonded joints was created.

Hybrid FSW and adhesive bonding has shown to produce higher strength and more ductile lap joints than FSW only lap joints, although not as strong or ductile as adhesive bonded joints.

Sandblasting has proven to be an insufficient surface treatment for adhesive and hybrid FSW adhesive joints, as anodizing aluminum results in a thicker aluminum oxide layer, which results in better wetting and stronger bonds.

Single pass hybrid joints with continuous adhesive layer shown lower distortion levels than FSW only joints, for the same vertical force levels.

While in FSW joints, increasing the vertical force resulted in increased distortion levels in hybrid joints this relation is not so prevalent, with hybrid joints manufactured with pre made channels for the adhesive layer presenting similar or lower values of distortion with increased vertical force.

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