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Cite as: AIP Conference Proceedings **1960**, 050011 (2018); https://doi.org/10.1063/1.5034884
Published Online: 03 May 2018

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Hybrid FSWeld-Bonded Joint Fatigue Behaviour

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Abstract. Aluminium alloys, widely used in aeronautics, are increasingly involved in the automotive industry due to the good relationship between mechanical strength and specific weight. The lightening of the structures is the first objective, which allows the decreasing in the weight in motion. The use of aluminium alloys has also seen the introduction of the Friction Stir Welding (FSW) technique for the production of structural overlapping joints. FSW allows us to weld overlap joints free from defects, but with the presence of a structural notch further aggravated by the presence of a "hook" defect near the edge of the weld. Furthermore, FSW presents a weld penetration area connected to the tool geometry and penetration. The experimental activity will be focused on the combination of two different joining techniques, which can synergistically improve the final joint resistance. In particular, the welding and bonding process most commonly known as weld-bonding is defined as a hybrid process, as it combines two different junction processes. In this paper we analyse FSWelded AA6082 aluminium alloy overlapped joint with the aim of quantitatively evaluating the improvement provided by the presence of an epoxy adhesive between the plates. After optimising the weld-bonding process, the mechanical behaviour of welded joints will be analysed by static and dynamic tests. The presence of the adhesive should limit the negative effect of the structural notch inevitable in a FSW overlapped joint.

INTRODUCTION

The world of transport always has an eye on new materials or new technologies that allow reduction of the weight of structures in order to improve energy efficiency.

One of these technologies is Friction Stir Welding (FSW), a process developed by the TWI [1] which, thanks to a solid-state joining process, allows materials to be joined at temperatures below their melting point. FSW presents many similarities with a conventional milling process. Indeed, the joint is made using a special tool which during roto-translation has the task of plasticising and mixing the material. The mechanical characteristics of FSW joints depend strictly on the welding parameters such as the tool rotation speed, the translation speed and the applied vertical force [2]. The use of the correct combination of parameters allows one to obtain joints free of defects. The material, not melting, has tensions and reduced distortions. Moreover, the absence of filler material allows one to obtain a surface finish of the flattened joint similar to a milling. Thanks to these characteristics, previously non-weldable materials can be joined together and among these aluminium alloys definitely stand out. There is ample literature that describes both the process and its application in cases of industrial interest [3].

The FSW process, by its very nature, lends itself very well to welding in a butt-joint configuration, since the action of the tool is perfect for mixing two materials that are placed side by side on the same plane. Some problems arise when welding in a lap-joint configuration, in this case the materials to be welded are superimposed and, therefore, material must be transported from top to bottom and no more from right to left (or vice versa)[4]. For this reason, a limited mixing zone is generated in the separation plane between the sheets having a particular hook shape [5]. This defect is very dangerous, as it constitutes a preferential path for the propagation of cracks and, moreover, is a dangerous

Proceedings of the 21st International ESAFORM Conference on Material Forming
AIP Conf. Proc. 1960, 050011-1–050011-6; https://doi.org/10.1063/1.5034884
Published by AIP Publishing. 978-0-7354-1663-5/$30.00

trigger for localised corrosion phenomena. Furthermore, this defect determines the resistance of the weld bead and in particular strongly limits its resistance to fatigue.

Another technology, of more ancient conception, which arouses much interest for the possibility of lightening structures, is bonding. Bonding is becoming increasingly affirmed in the field of structural joints. The use of adhesives has several advantages, including the possibility of combining very thin particulars without distortion, made with the most disparate materials, even different from each other, creating complex geometries [6]. Moreover, a bonded joint guarantees a uniform distribution of the stresses and therefore absence of strain concentrations in the adhesives. In recent years, structural bonding has undergone an important evolution thanks to the formulation of new adhesive compounds that allow one to obtain joints capable of withstanding even very high stresses, in difficult environmental conditions. Also in this field research is very active both on the intrinsic properties of adhesives and on their applicability in joints that involve different materials [7].

For the union of metallic materials there is a hybrid method in which the pieces are both welded and bonded together: this technique is called *weld-bonding*. By using the two joining processes together, it is assumed that the advantages of the single techniques synergistically add to each other, so as to reduce to the minimum the disadvantages of welding or bonding in their own right.

The high tensile and peel strength provided by welding is combined with the excellent fatigue strength and the uniformity of the load offered by the bonding. Initially developed in the former Soviet Union in the construction of the fuselage of the Antonov An-24 military transport aircraft, the weld-bonding technique has found a place in the automotive industry as well as in the aeronautics sector. In most cases there are couplings between Resistance Spot Welding (RSW) and adhesives of various kinds [8-9].

In this work, hybrid joints will be made by inserting an epoxy adhesive in FSWelded joints thus obtaining Friction Stir Weld-bonded joints. The effects of the presence of the adhesive in the welded joint will be evaluated by measuring the mechanical resistance. Once the optimal parameters have been identified, a series of joints will be created to be subjected to fatigue testing in order to trace the SN curve.

MATERIALS AND METHODS

The material used for this study is a 6082 alloy in the form of 2 mm thick sheet metal. The AA6082 (Tab.1) is a precipitation hardening aluminium alloy containing silicon, magnesium and manganese normally used in the naval and automotive sectors because it is characterised by good mechanical resistance values, excellent resistance to corrosion, excellent weldability and good workability with machine tools. The mechanical properties of the base material are shown in Table 2.

wt.%	Si	Mg	Mn	Cu	Fe	Cr	Zn	Ti	other	Al
AA6082	0.7-1.3	0.6-1.2	0.4-1.0	0.1	0.5	0.25	0.2	0.1	0.15	balance

TABLE 1. Chemical composition of AA6082 (mean values)

	Tensile Strength, Ultimate [MPa]	Tensile Strength, Yield [MPa]	Elongation at Break [%]	Young's Modulus [GPa]
AA6082	290-310	250-260	10	70

TABLE 2. Mechanical Properties of AA6082 (mean values)

The sheet was cut and prepared in pieces 250mm in length and 100mm in width. The welds were carried out in the direction perpendicular to the rolling direction using a dismountable tool with flat shoulder in hardened steel (ø = 19mm) and threaded conical tip in tool steel. The height of the pin was fixed in order to create a transparency junction so that the penetration involved both the overlapping sheets.

The parameters used to make the defect-free welds were identified during a previous test campaign. The rotation speed of the tool used was 630 rpm, the feed speed was 260 mm/min and a tool tilt angle of 2°.

The adhesive used was the 3M-DP490, a two-component epoxy resin that reticulates at room temperature. The surfaces of the samples were appropriately treated in order to remove any contaminants and obtain an optimal surface roughness. The samples were degreased with a cloth soaked in acetone and then abraded by sandblasting with corundum (220 grit).

The application of the adhesive was performed in three different conditions in order to identify the best possible solution. In the first case, the adhesive was applied over the overlapped area and the welding was carried out (Fig. 1a), in the second case the adhesive was applied only on the overlapping areas not affected by the welding (Fig. 1b) finally, in the third case, the adhesive was applied after welding. In the last case, to guarantee the necessary gap for the adhesive application it was necessary to mill the sheets removing 0.5mm of material from both plates (Fig. 1c). The penetration of the adhesive into the milled cavity was ensured by the forced injection of the adhesive by means of a pneumatic gun equipped with a needle. With repeated injections of adhesive the entire milled cavity was completely filled with adhesive In addition to the welded and glued joints, a set of welded samples and a set of bonded samples were created.

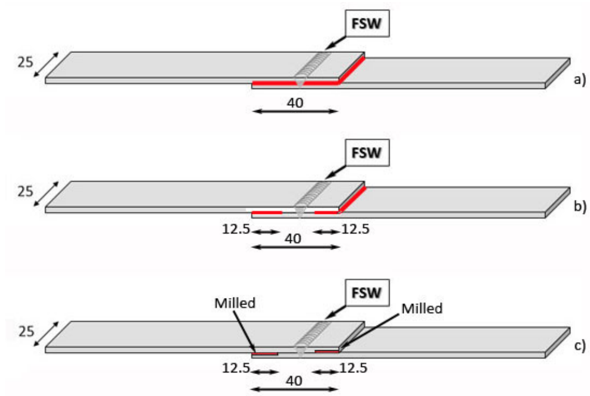


FIGURE 1: Overlapped joint overview

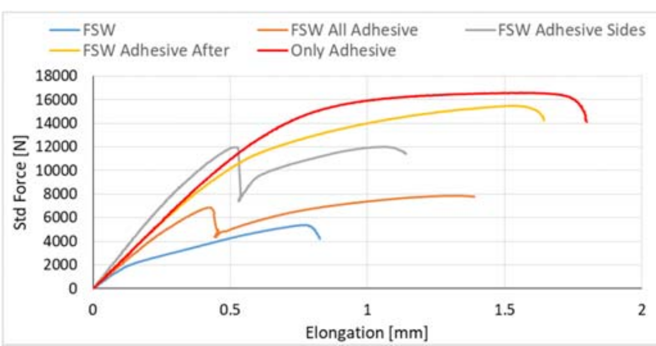
The joints were subjected to visual examination and tensile tests were performed on the cross section of the joint with a test speed of 5mm/min in order to evaluate the efficiency of the joint.

Once the best solution had been identified, a series of FSWeld-bonded plates and a single welded series were realised to be submitted to fatigue tests. These tests were performed with an Instron 8801 hydraulic servo with sinusoidal variable axial load with $R=\sigma_{min}/\sigma_{max}=0.1$ at a frequency of 5Hz at room temperature. The tests were carried out on samples 25mm wide and 160mm long, on which no mechanical processing was performed to remove the surface irregularities of the weld bead.

RESULTS

Static test

In the first phase of the study, 5 samples for each condition described above were used to perform the static tests and to perform the mechanical characterisation. The values obtained from this characterisation are expressed in Newtons because it is not possible to establish the effective resistant area. Figure 2 shows the results of the tests.



Overlap joint type	Std force max [N]	Elong [mm]
FSW	5389.36	0.77
FSW All Adhesive	7869.06	1.33
FSW Adhesive Sides	12011.92	1.06
FSW Adhesive After	15490.72	1.54
Only Adhesive	16583.74	1.56

FIGURE 2: Tensile test trend results with respect to the type of joint

It should be noted that the trend of the tensile tests for the joints in which the adhesive was applied before welding over the entire surface shows a peak at the failure of the bonding. After the bonding has yielded, there is only the resistance of the welding. This behaviour is due to the deterioration suffered by the adhesive during welding. In fact, during the realisation of the welds, the heat wave generated invests the adhesive, degrading it in the part between the plates directly under the tool shoulder. Even for samples where the adhesive was applied only on the sides, there is a strong deterioration due to the heat wave of the welding. In both cases the adhesive is completely cross-linked with the presence of gas bubbles inside it as soon as the welding is done. The high reticulating speed is not beneficial for an adhesive that normally reticulates in 7 days. The samples previously welded and then bonded have a continuous pattern with higher mechanical resistance values since the adhesive in this case does not undergo any kind of alteration. All FSWeld-bonded joints have values of mechanical strength higher than that only welded. The glued joints have higher resistance values because the entire overlap is covered by the adhesive.

Figure 3 shows the fracture surfaces of the FSW, bonded and FSWeld-bonded samples. The samples only welded or bonded are visible respectively in Figures 3a and 3e. The sample bonded on the whole surface and then welded (Fig. 3b) shows an evident lack of mixing caused by the presence of the adhesive which opposes the passage of heat from the upper sheet to the lower one during welding. This behaviour was also observed by Braga et al. [10] In this case, in addition to having degraded the adhesive, there is not correct welding between the parts. In case the adhesive is applied only on the sides (Fig. 3c) the welding appears correct, but also in this case the adhesive is badly damaged. The application of the adhesive after welding (Fig. 3d) makes it possible to obtain a well-performing joint with no obvious defects.

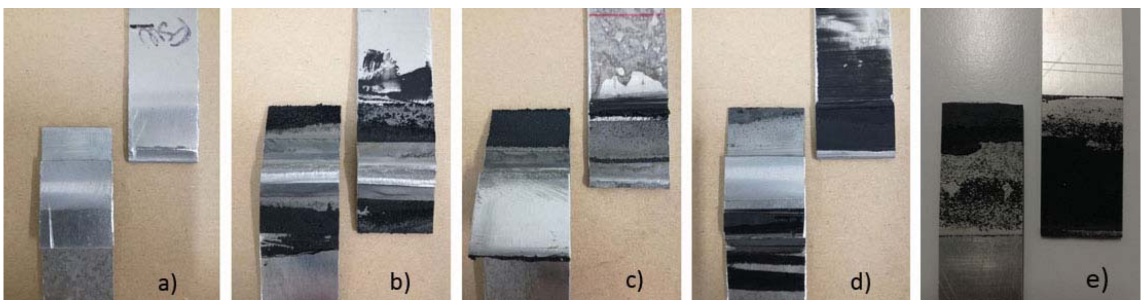


FIGURE 3: Tensile test fracture surface

Fatigue test

Fatigue tests were performed only on FSW joints and on FSWeld-bonded joints where the adhesive was applied only after welding. From the results of the static mechanical tests, the loads to be applied during the fatigue tests on both types of joints were selected: FSW and FSWeld-bonded. A mean force Fm = 2954N and 3 different stress amplitudes Fa, 2500N, 2000N and 1477N were adopted. For each of the Fa levels, 3 samples were tested. Figure 4 shows the comparison of fatigue test results on FSW joints and FSWeld-bonded joints.

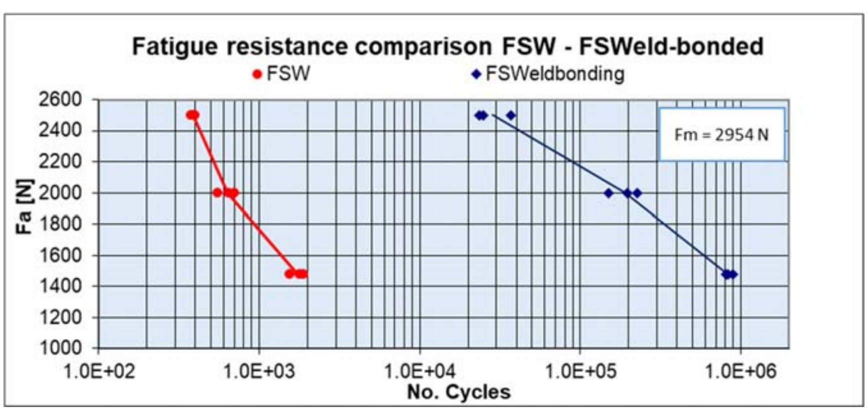


FIGURE 4: Fatigue resistance - Comparison between FSW and FSWeld-bonded

Figure 5 shows the position in which the failure occurred during fatigue testing of the FSW (Fig. 6a) and FSWeld-bonded joints (Fig. 6b).

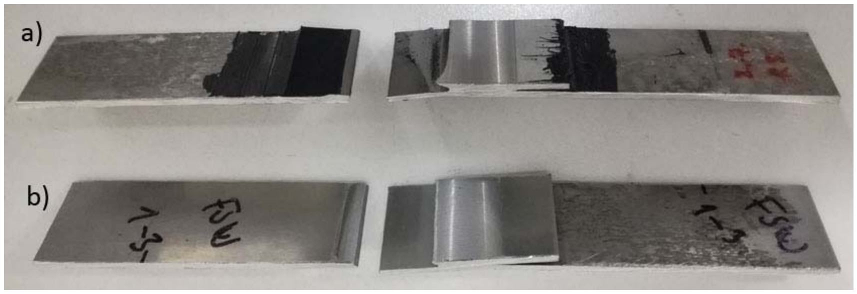


FIGURE 5: Comparison between (a) FSW and (b) FSWeld-bonded dynamic fractures

As can be seen, the breakage occurs in the upper sheet, outside the area where the material has been mixed. This shows that the chosen parameters allow us to reach the optimal welding conditions. As expected, the break occurred on the weld advancing side. Observing the fracture surfaces, it is evident that the fracture is ductile and occurs in the Heat Affected Zone (HAZ) where the temperature during welding produced an annealing effect of the aluminium alloy with the consequent loss of the ageing condition. In addition, the grain size in the HAZ is higher than that of the grains in the stirred zone where a dynamic recrystallization has occurred. Thus, the combination of annealing and grain enlargement explains the causes of the breakdown in the HAZ.

FSWeld-bonded joints subjected to fatigue testing with the same loads used for joints only FSWelded behave very differently. The morphology of the overlapping FSW joint is characterised by the presence of a notch at the interface between the two plates. This notch is very critical because its role is fundamental in triggering the crack that will break the joint. In contrast, in the FSWeldbonded joints the adhesive is opposed to cracking at the notch, ensuring an improved fatigue strength. This behaviour was also highlighted during previous research work where FSW welded joints and bonded joints were compared [11].

It should also be noted that the deformation of the plates in the two cases is very different. In the FSW joint, plastic deformation is much more pronounced than in FSWeld-bonded joints. This behaviour shows that during the test the misalignment of the force and the consequent moment arising is acting on the junction deforming it, transforming a shear stress into a combination of cutting and peeling. Peeling greatly reduces the mechanical strength of the joint. In the case of the FSWeld-bonded joint, this combination is very limited due to the presence of the adhesive.

Finally, a further phenomenon which confirms that the presence of the adhesive between the plates is positive concerns the advancement of the crack during the test. In the joints only FSWelded, once the crack is primed it progresses very quickly and within a few cycles a break is reached, while in the FSWeld-bonded joints you can observe the phenomenon of crack propagation since once triggered it progresses slowly thanks to the damping action of the adhesive. Figure 6 shows the crack during its progress.

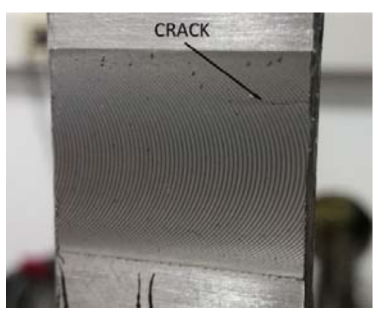


FIGURE 6: Fatigue crack in a FSWeld-bonded joint

SUMMARY AND CONCLUSION

In this work, different methods of making FSWeld-bonded overlapping joints were compared by performing tests on 2 mm thick AA6082 sheets. The study carried out made it possible to analyse the problems and underline the advantages in the use of FSWelded and bonded hybrid joints.

The realisation of FSWeld-bonded joints adopting the FSW technique presents some problems. The application of the adhesive before welding is certainly very simple, but it is very problematic since the development of the heat wave necessary for welding is inevitably destructive for the adhesive which does not withstand such thermal loads. The application of the adhesive following welding must presuppose the mechanical working of the flaps which guarantee the presence of the gap necessary to house the adhesive. The adhesive must also be fluid enough to penetrate between the welded plates. This last solution is very complex but it is the only one that allows one to exploit the two technologies fully.

The presence of the adhesive allows one to obtain a different behaviour of the joint both with respect to static and dynamic loads. Indeed, only FSW welded overlapping joints are strongly weakened by the presence of a structural notch at the interface between the welded sheets and the addition of adhesive delays the formation of cracks.

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