T JOINTS IN ALUMINIUM ALLOYS: STIFFENED PANELS BY FRICTION STIR WELDING

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SYNOPSIS

Friction Stir Welding (FSW) technology has shown a great potential for the manufacturing of structural parts in aluminum alloys due to the advantages offered by the technology. Most of the research works and applications developed since the invention of the technology have focused in butt joint configurations although some other configurations such as lap or T joints are highly interesting too. FSW of T joints has a great potential for stiffened panel construction in sectors such as aeronautic or marine. However the issues related to the technology are significantly different when dealing with T joints from those related to butt joints. Thus the implications regarding the tool design, welding parameters, etc need to be considered as shown by other authors [1-7].

The results of a research work investigating manufacturing and performance of T joints by FSW technology are discussed in this paper. The main objective of the work was to investigate the feasibility of FSW technology to produce T joints in aluminum alloys and compare to other existing joining technologies. FSW joints have been performed in T joint configuration with AA6082-T6 aluminium alloy. Those joints have been made using different welding parameters (rotational speed, welding speed, axial force, …) in a ISTIR PDS 4 machine specific for FSW. Single piece tools have been used creating the joint in the sheet/stiffener interface after penetrating through the sheet thickness. The weld quality has been evaluated by means of microstructural analysis and mechanical testing. Metallographic sections of joints made under different welding conditions have been studied by optical microscopy. Additionally, the mechanical properties of the joints have been evaluated by tensile testing.

The results show a very strong effect of the welding parameters in the formation mechanisms of the joints. The influence of the tool geometry is discussed based on metallurgical features produced by different features of the tool design and welding parameters. Thus material flow around the tool has been analysed and related to defect formation for T joint configurations. The relationships between defect formation and mechanical properties of the joints, and conditions where critical defects can be avoided have been established. Microstructural evolution of the joints is discussed focusing on the different microstructural zones that are present in the joint sections and their relationship with the welding parameters.

INTRODUCTION

The FSW process has shown its ability to produce lightweight structures in aluminium alloys as applications for the transport market. One example of such applications are ship sections manufactured by FSW exhibiting benefits such as reduced residual stresses and distortions [8]. Those benefits can allow reductions in welding times, manual fit up and general manufacturing costs compared to traditional fusion welding technologies in manufacturing of panels reinforced with stringers, which are based in skin to stringer joining in T-joint configurations.

FSW is the most significant development for aluminium alloy joining in approximately the last two decades and the technology has been extensively developed achieving high levels of process development. However that is not the case for T-joint configurations as few works have focused in this type of joint [1-7] and all of them have been carried out for relatively small thicknesses. In these research works it has been shown that particular issues such as the design of fixtures, FSW tools and welding parameters are key factors that need to be developed in order to avoid the formation of characteristic defects related to FSW of T joints such as tunnel defects or kissing bond defects.

In this work the formation of the mentioned tunnel and kissing bond characteristic defects characteristic for T-joints has been studied for relatively thick aluminium alloy sheets. The main objective is to obtain a better understanding of plasticized material flow produced by the FSW tools operated at different welding parameters and their relationship with defect formation and the properties of the joints.

EXPERIMENTAL PROCEDURE

FSW tests have been carried out in T joint configuration as shown in the schematic representation in Figure 1 and the images shown in Figure 2 and Figure 3. An adaptive fixture has been used so that aluminium sheets of different thicknesses can be clamped by separating side clamps. Thus 2 different thickness combinations of AA6082-T6 aluminium alloy sheets have been studied:

- 3 mm thick skin/6 mm thick stringer (“3/6” combination)
- 10 mm thick skin/10 mm thick stringer (“10/10” combination)

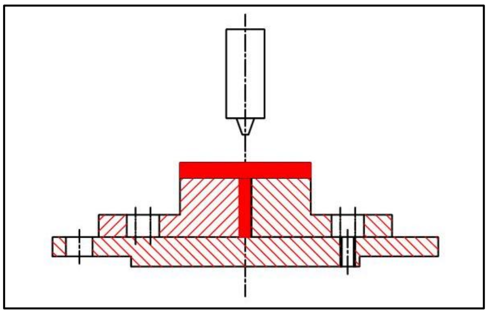

Figure 1: Clamping system for T joints.

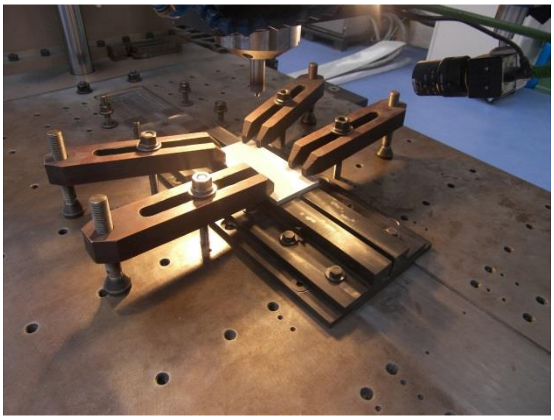

Figure 2: Aluminium sheets clamped in adaptive fixture for T-joints.

Figure 3: FSW of T-joint in progress.

Two different FSW tools have been used for the 3/6 and 10/10 material combinations with the following basic geometrical features:

- 3/6 combination
    - Shoulder: Cylindrical plain; Ø12 mm.
    - Probe: Cylindrical threaded; M4; 3,5 mm long.
- 10/10 combination
    - Shoulder: Cylindrical plain; Ø25 mm.
    - Probe: Cylindrical threaded; M8; 10,65 mm long.

All experiments have been performed at IK4 LORTEK Research Centre (Ordizia, Spain) using an ISTIR PDS 4 FSW machine (Figure 4). The Advanced MTS application software and the TestStarTM controller have enabled continuous data acquisition and management of the key FSW process parameters.

Figure 4: ISTIR PDS 4 FSW machine.

T-joints have been performed under different FSW process parameters for both thickness combinations. The main FSW parameters studied have been the rotational speed (RS) and welding speed (WS) while other process parameters have been kept constant such as the tilt angle which has been set to 1,5º for all welding tests. All tests have been performed in force control adjusting the axial force applied during FSW to ensure a good contact between the shoulder of the FSW tool and the surface of the top sheet. The investigated FSW parameter combinations have been:

- RS: 1000, 1500 and 2000 rpm
- WS: 150, 250 and 500 mm/min

An example of the T joints produced using one of those parameter combinations is shown in Figure 5 and Figure 6.

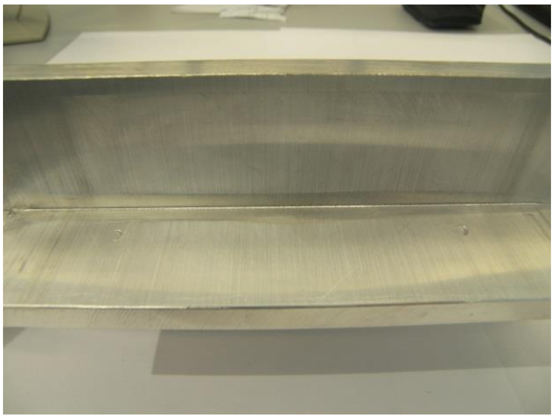

Figure 5: Fillet zone of the T joint specimen produced at 1000rpm; 250mm/min; 16kN.

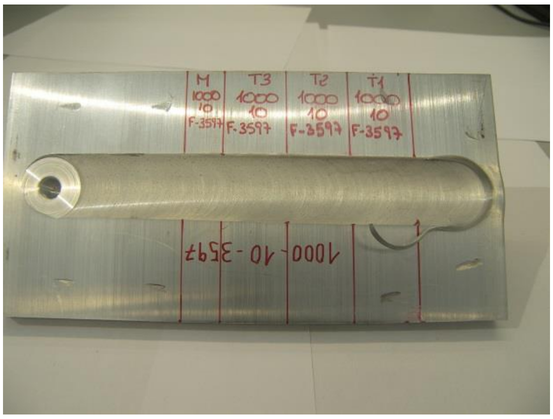

Figure 6: Top surface of the T joint specimen produced at 1000rpm; 250mm/min; 16kN.

For each specimen produced using different FSW parameters, metallographic sections have been polished, etched by a chemical reagent and examined by means of optical microscopy. In addition to this, mechanical strength has been investigated by stringer tensile testing (Figure 7) and skin tensile testing (Figure 8).

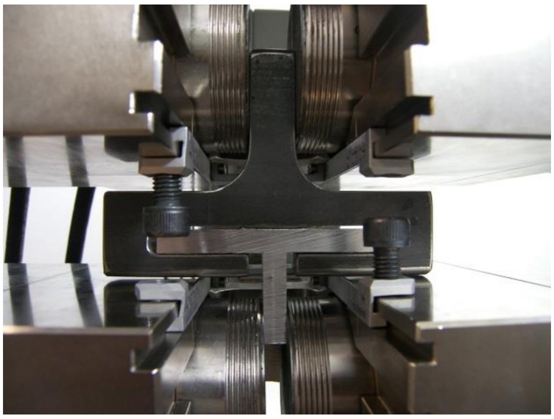

Figure 7: Stringer tensile testing set-up.

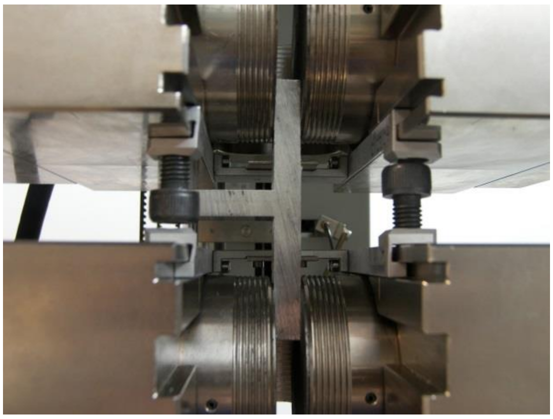

Figure 8: Skin tensile testing set-up.

RESULTS AND DISCUSSION

The results of the metallographic analysis carried out with T-joints produced in 3/6 combination are shown in Figure 9, Figure 10 and Figure 11. No tunnel defect has been found in any of the joints performed using all analysed welding parameter combinations. However, kissing bond type flaws have been found in all analysed cross sections in both advancing and retreating sides of the joints. Those kissing bonds present their origin at the fillet corner between the skin and the stringer and grow towards the stir zone.

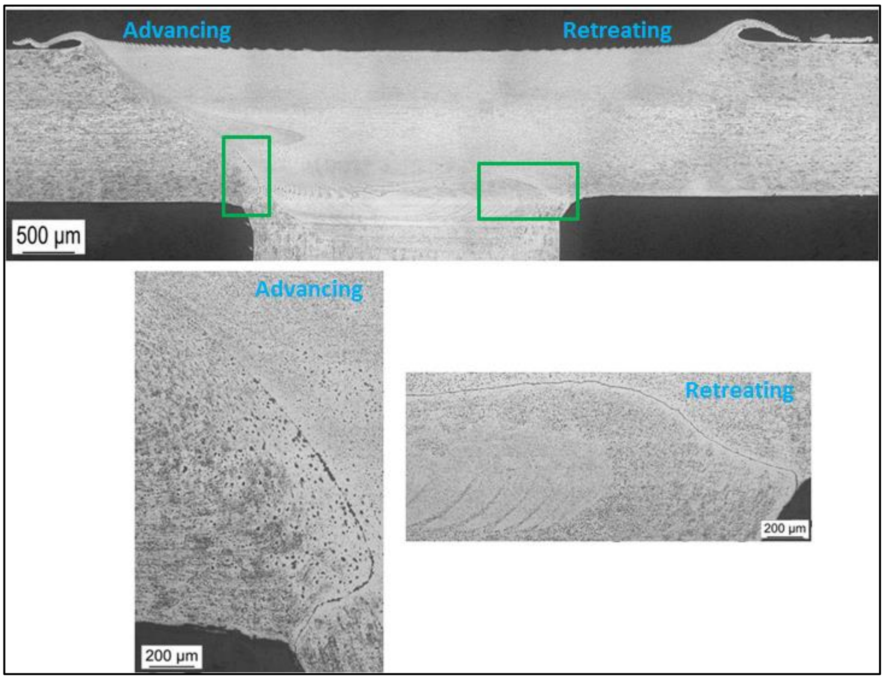

Figure 9: Cross section of 3/6 combination T-joint produced by FSW at 1000rpm; 150mm/min; 6,4 kN.

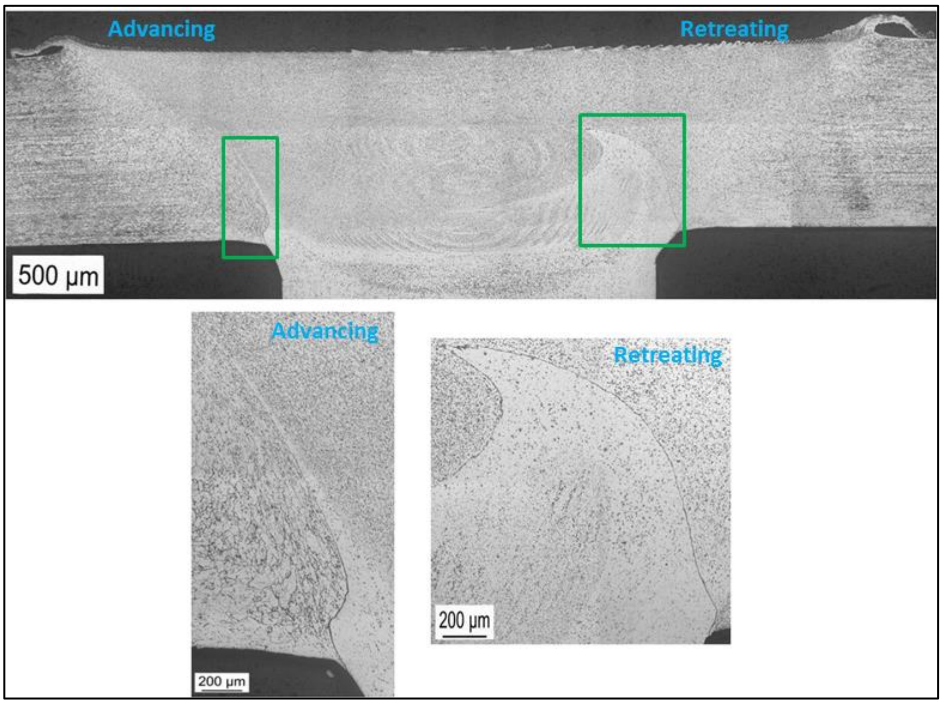

Figure 10: Cross section of 3/6 combination T-joint produced by FSW at 1500rpm; 150mm/min; 5,1 kN.

It has been found the welding parameters have a very important influence in the size and shape of the kissing bonds present in the fillet corners. The use of relatively low welding speeds (150 mm/min) promotes the upwards movement of the kissing bond in both advancing and retreating sides, being this movement larger if high rotational speeds are used (Figure 9, Figure 10). Therefore FSW performed in “hot conditions” (when the mm/revolution rate is low) produce larger kissing bond flaws and this effect is associated to the enhanced vertical material flow forced by the threaded tool at “hot condition”. When the welding speed is increased (500 mm/min), the shape of the kissing bonds present at both advancing and retreating sides change to a more horizontal shape, showing a lower vertical material flow imposed by the threaded tool (Figure 11).

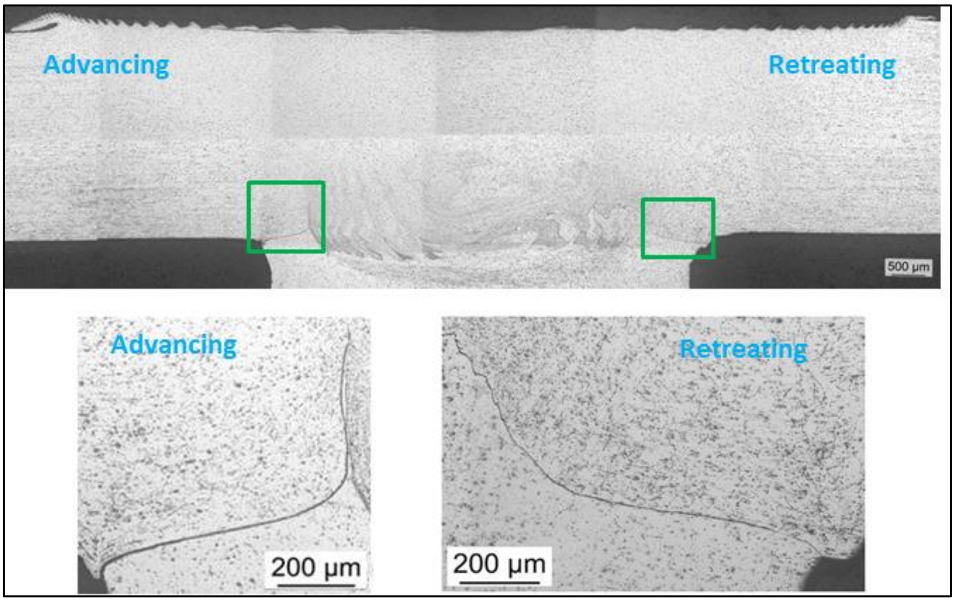

Figure 11: Cross section of 3/6 combination T-joint produced by FSW at 1500rpm; 500mm/min; 6,7 kN.

Table 1: Resistance of 3/6 combination T-joints in stringer tensile testing.

CONDITION	WELDING PARAMETERS			MAXIMUM FORCE Avg (kN)
	RS (rpm)	WS (mm/min)	F (kN)	
C1	1000	150	6,4	11,6
C2	1500	150	5,1	9,6
C3	1500	500	6,7	12,4

The shape of the kissing bond flaws have been found to present its influence in the mechanical resistance of the 3/6 combination T-joints in stringer tensile testing as shown in Table 1. Thus condition C2 produced under the lowest mm/revolution rate has shown the lowest average resistance value of 9,6 kN. On the contrary, condition

C3 produced with largest mm/revolution rate has shown the highest value of 12,4 kN. Therefore, as it could be expected, highest mechanical resistance values are associated to small kissing bond flaws which are generated at high mm/revolution rates.

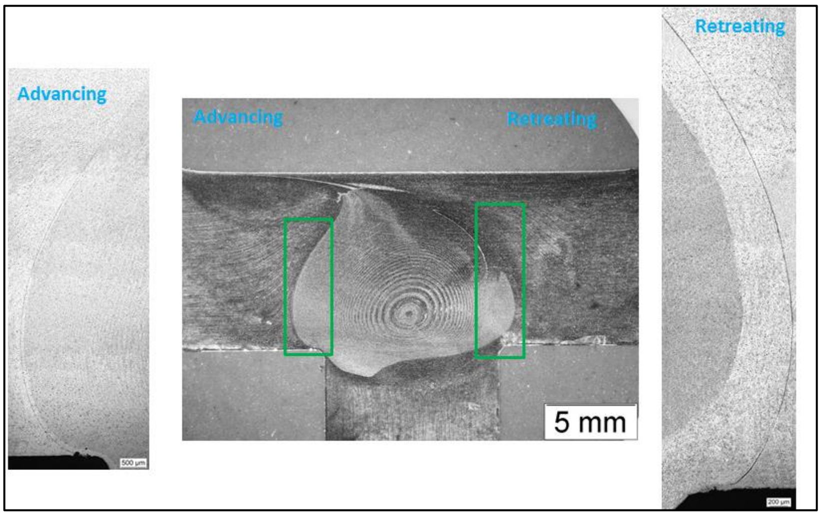

Figure 12: Cross section of 10/10 combination T-joint produced by FSW at 1500rpm; 150mm/min; 15 kN.

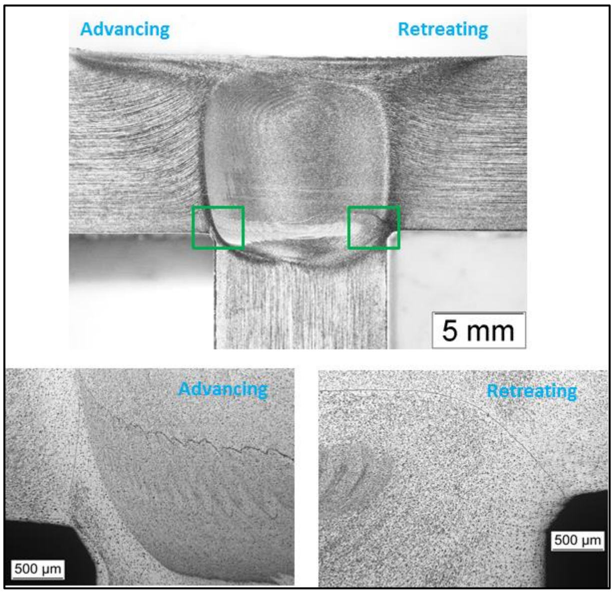

Figure 13: Cross section of 10/10 combination T-joint produced by FSW at 1000rpm; 250mm/min; 16 kN.

Similar results have been obtained for 10/10 combination T-joints (Figure 12 and Figure 13). T-joints produced using a relatively low welding speed and a high rotational speed show large kissing bond flaws in the advancing and retreating sides as can be observed in Figure 12. At these conditions, a clear onion ring pattern can be seen which is a typical metallurgical feature that is formed when threaded tools are operated at low mm/revolution rates ("hot conditions"). The large thread dimensions of the tool used for 10/10 combination T-joints is responsible for the enhanced vertical flow of plasticized material that generates the vertical shaped large kissing bonds. This vertical plasticised material flow is reduced when the rotational speed is reduced and the welding speed increased (Figure 13). In these conditions the onion ring pattern hardly can be distinguished and much smaller kissing bond flaws can be observed in the advancing and retreating sides.

Table 2: Resistance of 10/10 combination T-joints in stringer tensile testing.

CONDITION	WELDING PARAMETERS			MAXIMUM FORCE Avg (kN)
	RS (rpm)	WS (mm/min)	F (kN)	
C4	1500	150	15	23,2
C5	1000	250	16	25,3

Table 3: Resistance of 10/10 combination T-joints in skin tensile testing.

CONDITION	WELDING PARAMETERS			MAXIMUM FORCE Avg (kN)
	RS (rpm)	WS (mm/min)	F (kN)	
C4	1500	150	15	17,6
C5	1000	250	16	43,1

The shape and size of the kissing bonds present in the T-joints have shown a large influence in the mechanical performance of the T-joints as shown in Table 2 and Table 3. Little influence has been observed in stringer tensile testing even though the lowest strength values have been found for T-joints presenting largest kissing bond flaws (Table 2). However, in skin tensile testing a very large influence of the shape of kissing bonds has been observed (Table 3). T-joints produced with conditions C4 (low mm/revolution rate) have shown a very low average value of 17,6 kN, while a significantly higher value of 43,1 kN has been measured for T-joints made under C5 conditions (high mm/revolution rate).

The fracture mode and fracture surface analysis of C4 and C5 specimens after skin tensile testing show the reason for the large difference in their mechanical performance (Figure 14-Figure 17). In Figure 14 the fracture of C4 specimens through the kissing bond present in the retreating side of the T-joints can be observed. The fracture surface of those specimens (Figure 15) shows an upwards deformation of the faying surface of the joint with no metallurgical bond except for the top part where the kissing bond flaw is missing (Figure 12). On the contrary, the fractured C5 specimen shown in Figure 16 exhibits a fracture through the HAZ of the advancing side with an initiation in the kissing bond present in that region. The fracture surface of this sample shows a full metallurgical bond in most of the section although a small region with no metallurgical bond can be observed in the fillet corner of the T-joint (Figure 17). As shown in Figure 13 this is the region where the kissing bond is present in the advancing side, being responsible for the lack of metallurgical bond present at this zone.

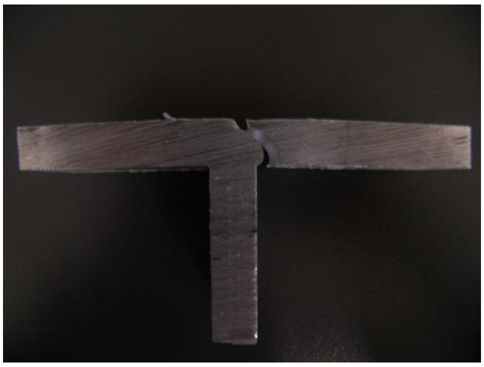

Figure 14: C4 specimen fractured in skin tensile testing.

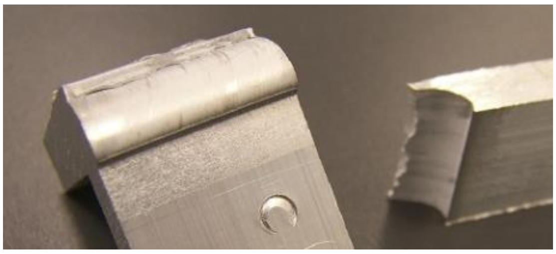

Figure 15: Fracture surface of C4 specimen fractured in skin tensile testing.

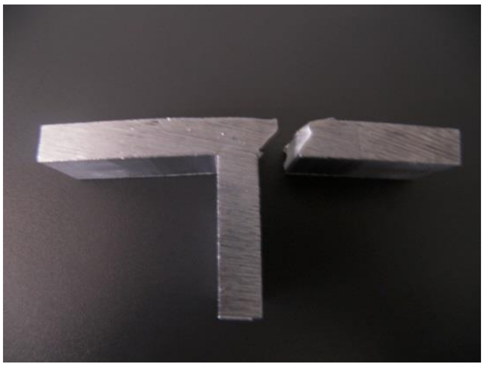

Figure 16: C5 specimen fractured in skin tensile testing.

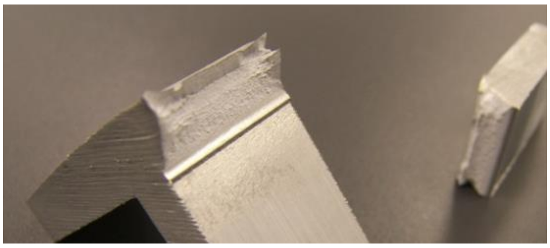

Figure 17: Fracture surface of C5 specimen fractured in skin tensile testing.

SUMMARY AND CONCLUSIONS

T-joints have been produced by FSW in 3/6 and 10/10 thickness configurations with AA6082-T6 aluminium alloys. Joint formation mechanics and mechanical evaluation of the joint strength have been performed obtaining the following conclusions:

- No tunnel defects have been found using a sharp fillet corner radius in all the range of investigated welding parameters.
- Kissing bond flaws have been observed in all the range of investigated welding parameters. The shape and size of those kissing bonds are largely dependent on the used welding parameters.
- T-joints produced by threaded tools with relatively low mm/revolution rates result in large vertical shaped kissing bond flaws. If relatively high mm/revolution rates are used smaller kissing bond flaws are developed.
- Little influence of the shape and size of kissing bond flaws has been observed in stringer tensile test results. Larger kissing bond flaws resulted in lower strength values.
- A large influence of the kissing bond shape and size has been observed in skin tensile testing results. T-joints exhibiting smaller kissing bond flaws have shown significantly higher strength values.

- Fracture surfaces of skin tensile tested specimens have shown a small metallurgical bonded area for T-joints produced using relatively low mm/revolution rates; whereas T-joints produced with relatively high mm/revolution rates have shown a significantly higher metallurgical bonded area.

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