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Friction stir weldbonding defect inspection using phased array ultrasonic testing

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Abstract

Weight reduction is an important driver of the aerospace industry, which encourages the development of lightweight joining techniques to substitute rivet joints. Friction stir welding (FSW) is a solid state process that enables the production of lighter joints with a small performance reduction compared to the base material properties. Increasing the FSW lap joint performance is an important concern. Friction stir weldbonding is a hybrid joining technology that combines FSW and adhesive bonding in order to increase the mechanical properties of FSW lap joints. FSW and hybrid lap joints were produced, using 2 mm thick AA6082-T6 plates and a 0.2 mm thick adhesive layer. Defect detection using the non-destructive test, phased array ultrasonic testing (PAUT), has been made. Microscopic observations were performed in order to validate the phased array ultrasonic testing results. Lap shear strength tests were carried out to quantify the joint's quality. PAUT inspection successfully detected non-welded specimens, but was not able to distinguish specimens with major hook defects from specimens correctly weldbonded with small hook defects.

Keywords: Friction Stir Welding, Hybrid joining, Friction Stir Weldbonding, Lap joining, Phased Array Ultrasonic Testing

1. Introduction

Friction stir welding (FSW) is a solid-state, environmentally friendly joining technique, capable of producing high quality joints with a small reduction in the mechanical performance compared to the base material, when used in butt configuration. In the aeronautic industry the butt configuration is not always the most appropriate joint type due to tolerance issues, although when used in lap joint configuration the mechanical properties of the joint suffer a significant decrease.

Ericsson et al. [1] carried out lap shear strength tests on AA6082-T6 FSW lap joints and reported this joints presented 55% mechanical efficiency when compared to the static strength of the base material.

To produce sound FSW lap joint vertical material movement is mandatory, since the surface to be welded is horizontal. Although vertical material flow is very important to produce sound FSW lap joints it is a complex and not completely understood subject. Furthermore vertical material flow is responsible for the creation of interface defects - hook defects - which are a common feature of FSW lap joints. Due to its configuration and orientation, these defects act as stress concentration factors/crack initiation [2, 3].

Several researches have been conducted in order to understand the fatigue properties of FSW single lap joints [4, 5]. Reis et al. [4] compared the fatigue strength of welded lap joints of AA6082-T6 produced by FSW and laser beam welding (LBW). The authors concluded that the LBW joints presented higher fatigue strength than the ones produced by FSW. Furthermore it was observed that the crack initiated at an interface defect of the FSW joint. Infante et al. [5] performed fatigue tests on similar and dissimilar FSW lap and butt joints, and concluded that the FSW lap joints presented much lower fatigue strength than butt joints. The authors stated that the presence of a hook defect on the FSW lap joints may be responsible by the inferior fatigue strength of these joints.

To overcome the mechanical properties of FSW lap joints, degraded by interface defects, an innovative hybrid joining process was proposed: friction stir weldbonding, consisting of the combination of FSW and adhesive bonding [6]. Braga et al. [6] produced friction stir weldbonding lap joints of AA6082-T6 using Araldite® 420 A/B adhesive. Single lap joints with 60 mm of overlap length were used and different surface treatment methods were tested - sandblasting and phosphoric acid anodizing. The lap shear strength tests performed showed that the hybrid joints presented higher ultimate tensile strength (UTS) than the FSW joints, but were not as strong as the adhesive bonded joints. Anodizing proved to be the best option for surface treatment, this process resulted in the formation of a thick aluminium oxide layer creating better wetting and stronger bonds.

In this research study hybrid friction stir weldbonding single lap joints of AA6082-T6 were successfully manufactured. Phased array ultrasonic testing (PAUT) was used to detect defects and the obtained results were correlated with microscopy analysis and lap shear strength tests. FSW joints were also manufactured and tested in order to compare with the results from hybrid joints.

PAUT has been successfully used as an in-line quality control of FSW butt joints regarding flaw detection [7]. Several NDT techniques (x-ray detection, fluorescent penetrating fluid inspection, ultrasonic C-scan and PAUT) were used to detect defects on FSW butt joints of AA2219-T6. PAUT revealed an outstanding performance in inspecting tight void defects by a single-pass scan [8]. Mandache et al. [9] reported that PAUT successfully detects lack of penetration defects on FSW butt joints. Das et al. [10] used ultrasonic C-scan and B-scan to inspect dissimilar (aluminium and steel) FSW lap joints and compared the results with x-ray radiography. They reported that the ultrasonic testing is useful to detect interface defects in FSW lap joints.

2. Implementation

2.1. Material Properties

The aluminium alloy 6082-T6 was used as base material through plates of 2 mm thickness. Its chemical composition and mechanical properties are presented in table 1.

Table 1 Chemical composition and mechanical properties of the AA6082-T6.

Chemical Properties	Al [wt %]	Cr [wt %]	Cu [wt %]	Fe [wt %]	Mg [wt %]	Mn [wt %]	Si [wt %]	Ti [wt %]	Zn [wt %]	Others [wt %]
	95.2-98.3	≤0.25	≤0.10	≤0.50	0.6-1.2	0.4-1.0	0.7-1.3	≤0.10	≤0.20	≤0.15
Mechanical Properties			Density [kg/m^3]	Vickers Hardness [HV]	Ultimate Tensile Strength [MPa]	Yield Tensile Strength [MPa]	Elongation at Break [%]			
			2700	95	290	250	10			

For the production of the hybrid friction stir weldbonded joints Araldite® 420 A/B was used as structural adhesive. Araldite® 420 A/B is a two component adhesive suitable to bond aerospace structures.

2.2. Joint Geometry and Production

Single lap joints were manufactured using FSW and friction stir weldbonding. FSW and hybrid joints were produced with 20 mm of overlap length.

Both types of joints were friction stir welded on a LEGIO^{TM} FSW 3UL numeric control machine from ESAB and the welding procedure was performed under forging force control. A robust clamping system was used to produce high quality joints. The tool used to weld both types of joints is composed of a flat scrolled shoulder and a threaded cylindrical pin, both shown in figure 1.

The shoulder used has a diameter of 16 mm while the pin has diameter of 5 mm.

(a) Shoulder (b) Pin

Figure 1 FSW tool used: flat scrolled shoulder and threaded cylindrical pin.

Hybrid friction stir weldbonding joints require both friction stir welding and adhesive bonding, so some extra procedures were performed. Since bonding strength between substrate and adhesive is critical, a good surface preparation is crucial. Prior to the adhesive application, surface treatment of the plates to be weld-bonded was performed - using phosphoric acid anodizing as a surface treatment following the standard D3933. FSW process must be performed immediately after the adhesive application. To overcome this constraint the adhesive application was done in the workbench of the FSW machine. After welding, the joints were left to cure the adhesive at room temperature for more than one week.

The joints produced are presented and described in table 2.

Table 2 FSW and hybrid produced joints.

Nomenclature	**Forging Force [N]**	**Welding Speed [mm/min]**	**Rotation Speed [rpm]**
FSW-1	3922.7	200	1000
FSW-1	4413.0	200	1000
Hyb-1	3530.4	200	1000
Hyb-2	3922.7	220	1000

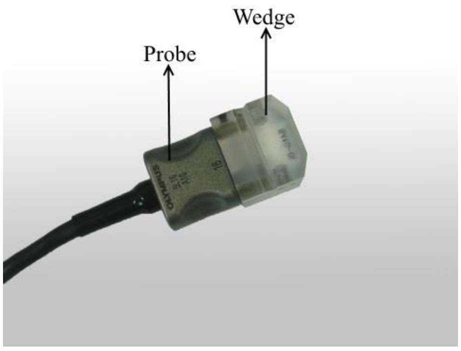
Hyb-3	3432.3	220	900
Hyb-4	3530.4	180	1000
Hyb-5	3922.7	200	1000

2.3. PAUT Inspection

In order to detect defects and flaws the joints were inspected using NDT technique. Phased array ultrasonic testing (PAUT) was the technique employed.

The OmniScan® SX by Olympus was used to inspect flaws in the FSW and in the hybrid joints. A Olympus small-footprint probe - 10L10-A0-TOP - 10 Mhz of frequency and 32 elements was used. A zero-degree wedge was attached to the probe during the inspections. The system used for the PAUT inspections is shown in figure 2. Before the inspection a water-based couplant was spread on the inspection area in order facilitate the transmission of sound energy from the probe to the workpiece. Since the FSW process produces certain protuberances on the top surface, the probe was placed on the surface opposite to the protuberances, i.e. the workpiece upside down.

(a) Olympus Omniscan® SX



(b) Probe and wedge assembled

Figure 2 System used for the phased array ultrasonic testing.

2.4. Microscopy Analysis

After the PAUT inspection, several sections of the joints were selected. The sections were selected either because a defect was detected or because it was a flawless section of the joint. Sections highlighted in the PAUT analysis were then examined under the optical microscope to validate the NDT inspection results. A stereo microscope Zeiss SteREO 95 Discovery.V8 and an inverted microscope Zeiss Axiovert 40 MAT were used. The first one was used to capture the macroscope images of the joints, while the Zeiss Axiovert 40 MAT captured the microscope details of the joints.

2.5. Lap Shear Strength Tests

Lap shear strength tests were conducted for specimens adjacent to the sections analyzed. These tests were performed in order to quantify the joints quality and correlate this results with the defect inspection results obtained before.

A testing machine INSTRON® 3369 with maximum load capacity of 50 kN with constant displacement rate - 1 mm/min - was used to perform the tests. Figure 2 shows the specimen's geometry used.

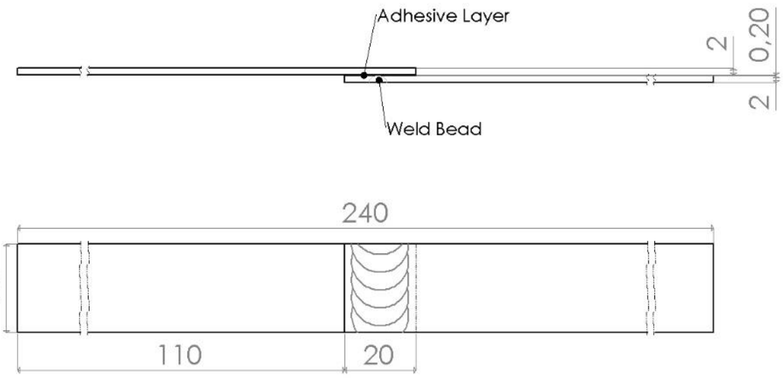
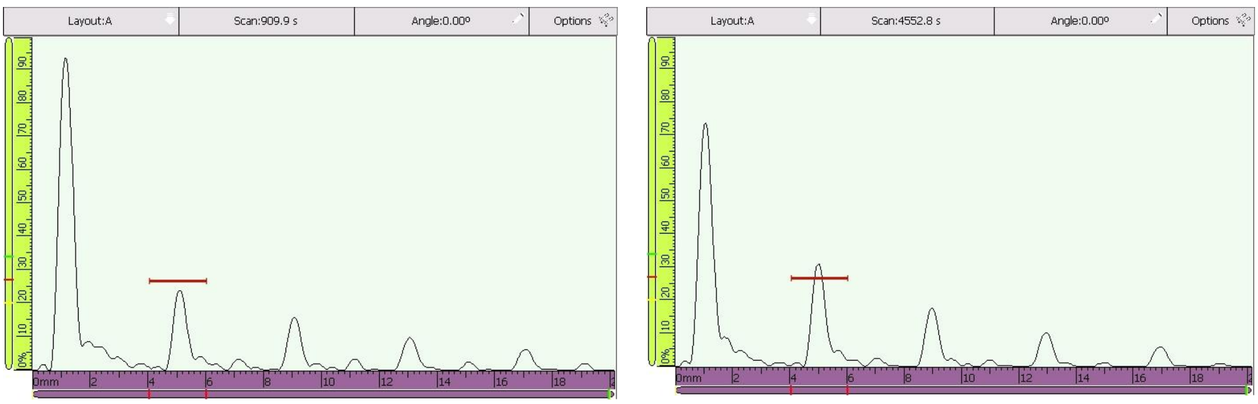


Figure 3 Specimen geometry.

3. Experimental Results

3.1. Phased Array Ultrasonic Testing

Firstly the FSW joints, FSW-1 and FSW-2, were inspected using PAUT. Figure 4 and Table 3 show the obtained results. No relevant reflections were observed along the thickness, indicating that these are defect-free welds.



(a) FSW-1 (b) FSW-2

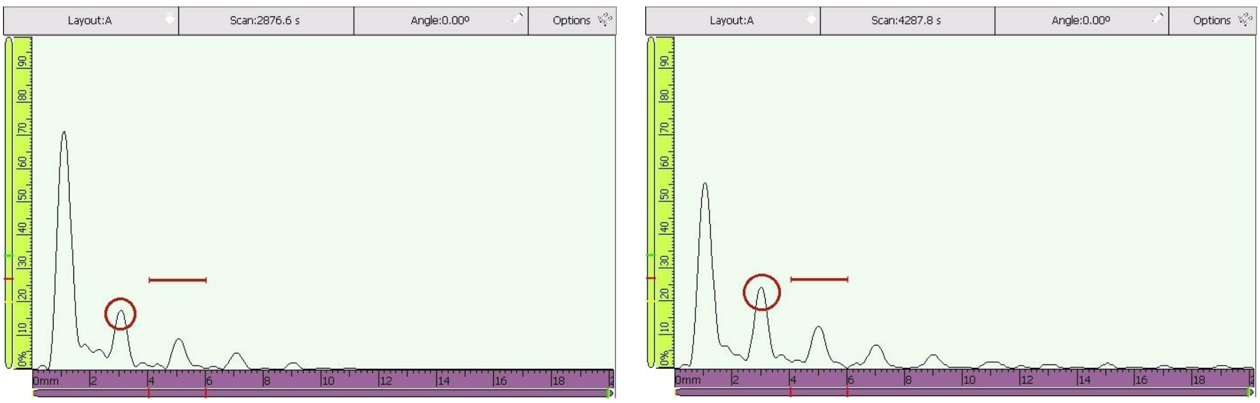
Figure 4 PAUT results obtained for the simply FS welded joints. Vertical scale is wave amplitude in percentage, horizontal scale is distance [mm].

Table 3 PAUT peaks characterization for joints FSW-1 and FSW-2.

FSW-1			
Peak	**Depth [mm]**	**Amplitude in percentage**	**Comment**
FSW-1-1	1.2	94	Surface Reflection
FSW-1-2	5.2	24	Back-wall Reflection
FSW-2			
Peak	**Depth [mm]**	**Amplitude in percentage**	**Comment**
FSW-2-1	1	74	Surface Reflection
FSW-2-2	5	31	Back-wall Reflection

Hybrid joints - Hyb-1, Hyb-2, Hyb-3, Hyb-4 and Hyb-5 - were also inspected by PAUT. The obtained results can be separated into two groups. The first group of joints revealed a reflection peak approximately at the middle of the joints thickness, while the second group presented a small reflection peak near the back-wall of the joints.

The information obtained from Figure 5 is summarized in Table 4. Figure 5 reveals a large reflection approximately at the middle of both joints' thickness for Hyb-1 and Hyb-3 (3.1 and 3 mm respectively). For joint Hyb-1 17% of the wave amplitude was reflected, while for Hyb-3 25% was reflected. This peak indicates a material discontinuity along the weld zone, which shows that in the interface of both joints an adhesive layer is present. The presence of an adhesive layer in the joints interface implies that the FSW tool was not able to disrupt the lap joint interface, due to low heat input created by the set of FSW control parameters used.



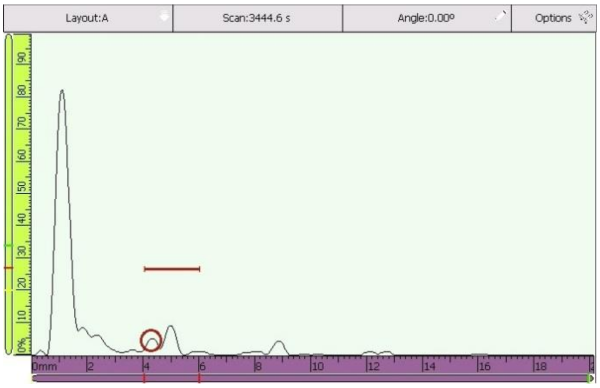
(a) Hyb-1 (b) Hyb-3

Figure 5 PAUT results obtained for hybrid specimens Hyb-1 and Hyb-3. The red circle signalizes the middle peak observed. Vertical scale is wave amplitude in percentage, horizontal scale is distance [mm].

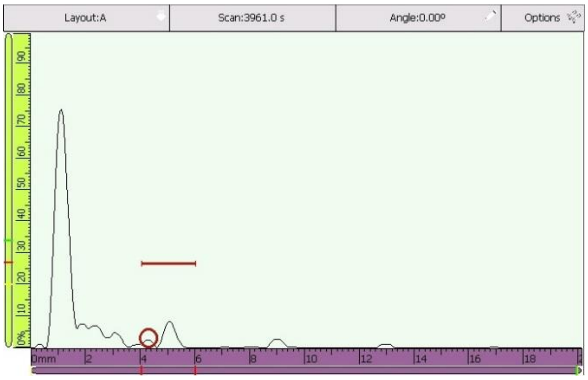
Table 4 PAUT peaks characterization for joints Hyb-1 and Hyb-3.

Hyb-1			
Peak	**Depth [mm]**	**Amplitude in percentage**	**Comment**
Hyb-1-1	1.2	71	Surface Reflection
Hyb-1-2	3.1	17	Mid Thickness Reflection
Hyb-1-3	5.1	9	Back-wall Reflection
Hyb-3			
Peak	**Depth [mm]**	**Amplitude in percentage**	**Comment**
Hyb-3-1	1	51	Surface Reflection
Hyb-3-2	3	25	Mid Thickness Reflection
Hyb-3-3	5	12	Back-wall Reflection

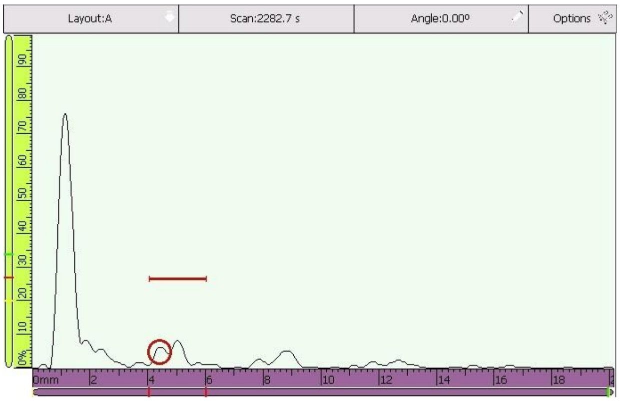
Specimens Hyb-2, Hyb-4 and Hyb-5 A-scans, shown in Figure 6, do not reveal any reflection at the middle of the joints, but a small echo is present near the back-wall reflection. Table 5 refers that 5%, 3% and 8%, respectively for joints Hyb-2, Hyb-4 and Hyb-5, of the wave amplitude was reflected. These peaks location is near the back-wall for every joint, more specifically, the peaks are located at 85%, 78% and 87% of the joint thickness respectively. Due to the material vertical movement that the FSW of lap joints demands, it is common that the interface of the joints is pushed upward. This movement leads to the formation of interface defects, typically hook defects. The fact that the reflected waves are located next to the back-wall is a clear indicator that specimens Hyb-2, Hyb-4 and Hyb-5 present hook defects.



(a) Hyb-2



(b) Hyb-4



(c) Hyb-5

Figure 6 PAUT results obtained for hybrid specimens Hyb-2, Hyb-4 and Hyb-5. The red circle signalizes the small peak observed. Vertical scale is wave amplitude in percentage, horizontal scale is distance [mm].

Table 5 PAUT peaks characterization for joints Hyb-2, Hyb-4 and Hyb-5.

Hyb-2			
Peak	**Depth [mm]**	**Amplitude in percentage**	**Comment**
Hyb-2-1	1.1	83	Surface Reflection
Hyb-2-2	4.4	5	Hook Reflection
Hyb-2-3	5	9	Back-wall Reflection
Hyb-4			
Peak	**Depth [mm]**	**Amplitude in percentage**	**Comment**
Hyb-4-1	1.2	75	Surface Reflection
Hyb-4-2	4.3	3	Hook Reflection
Hyb-4-3	5.2	8	Back-wall Reflection
Hyb-5			
Peak	**Depth [mm]**	**Amplitude in percentage**	**Comment**
Hyb-5-1	1.2	76	Surface Reflection
Hyb-5-2	4.5	6	Hook Reflection
Hyb-5-3	5	8	Back-wall Reflection

The PAUT results also show that the material discontinuities found are interface defects filled with adhesive. If it was air inside the interface defects, the sound wave would be almost completely reflected, since the acoustic impedance of aluminium and air are very different. It can be observed in the A-scans presented that only a small portion of the sound wave is reflected and the remaining is transmitted proving that a different material is inside the interface defect - in this case adhesive.

3.2. Microscopy Analysis

Microscopy analysis was performed on the same joints and locations previously inspected through PAUT, in order to understand the meaning of the PAUT results and how to use the PAUT results to properly evaluate the joints quality. Every image presented here is upside down (top surface of the joint on the bottom) to simplify the results comprehension, since the PAUT were also performed on the back surface of the joint.

The macroscopic and respective microscopic images of FSW-1 and FSW-2 joints are presented in Figure 7. No defects are present along the welds, as would be expected based on the PAUT results.

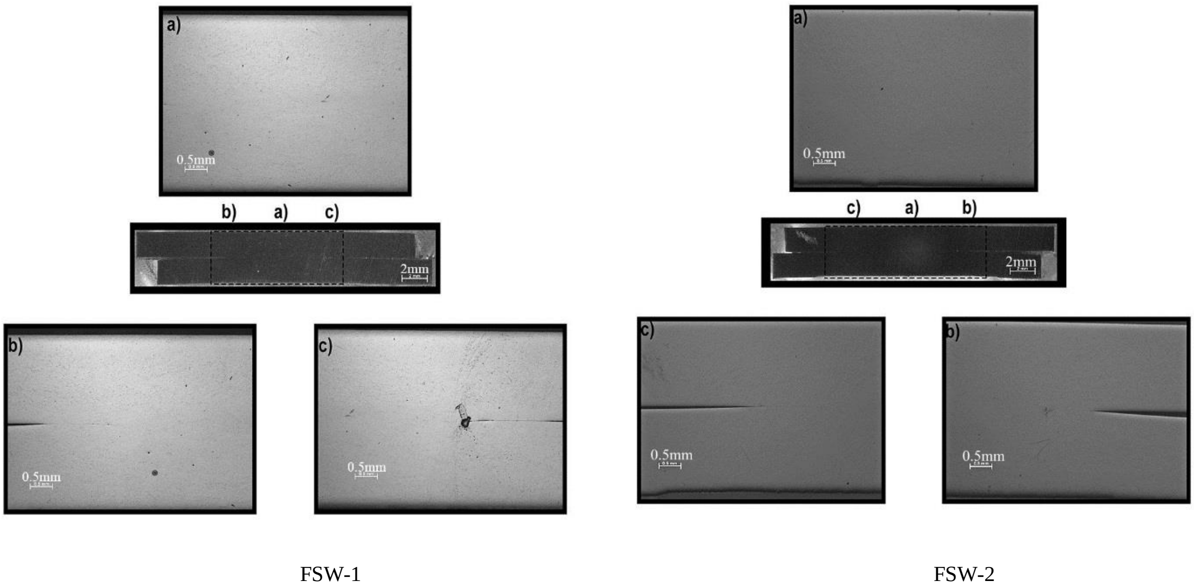


Figure 7 Macroscopic and microscopic figures of FSW-1 and FSW-2 weld cross section; a) center of the weld, b) retreating side and c) advancing side.

Hybrid joints Hyb-1 and Hyb-3 macroscopic and microscopic figures are presented in Figure 8. These observations show an almost continuous adhesive layer along the weld zone of both specimens. Based on the PAUT inspection it was expected that an adhesive layer was present in the middle of the joints thickness. Microscopic analysis corroborates the PAUT results.

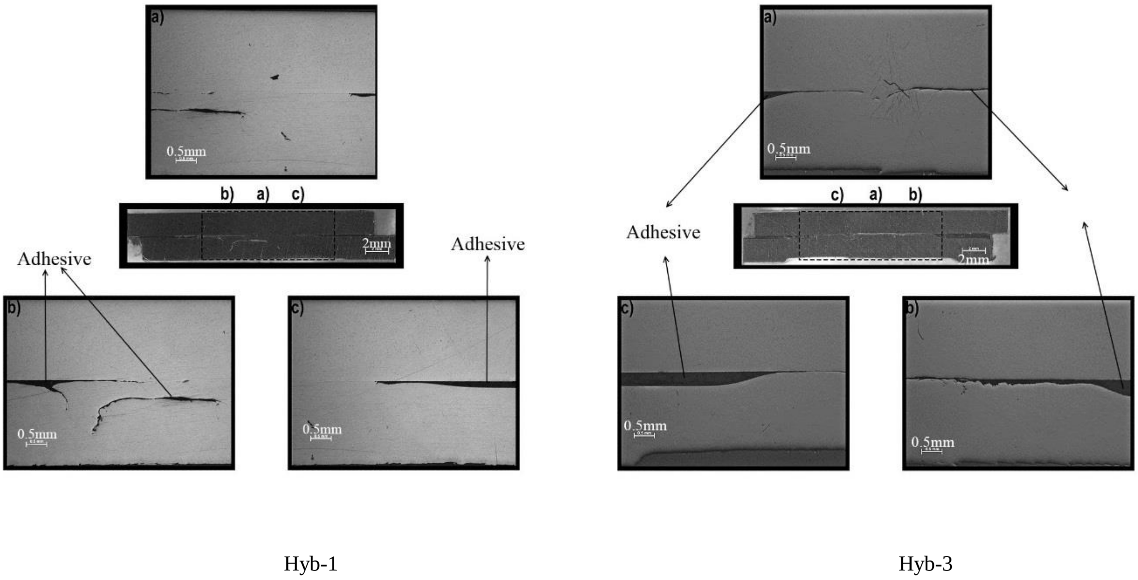


Figure 8 Macroscopic and microscopic figures of the Hyb-1 and Hyb-3 weld cross sections; a) center of the weld, b) retreating side and c) advancing side.

Specimens Hyb-2 and Hyb-4, shown in Figure 9, show massive hook defects filled with adhesive, located on the retreating side of the welds. PAUT results also indicated that these specimens presented interface defects (hook defects) filled with adhesive, as the microscopic observations show.

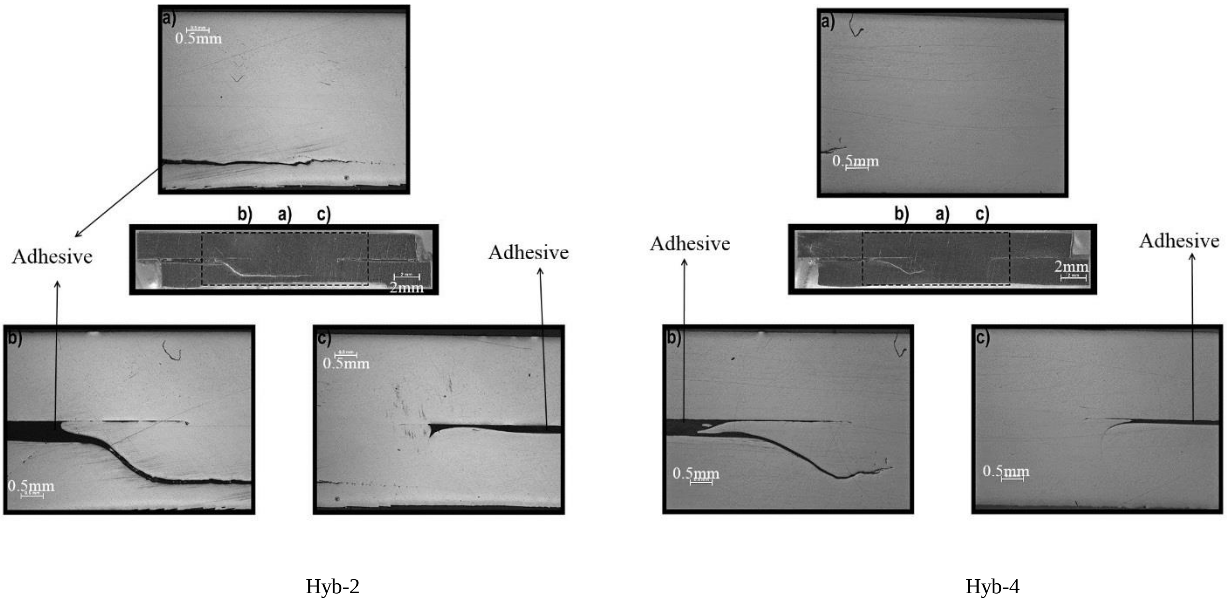


Figure 9 Macroscopic and microscopic figures of the Hyb-2 and Hyb-4 weld cross sections; a) center of the weld, b) retreating side and c) advancing side.

Figure 10 shows the macroscopic and microscopic images obtained for joint Hyb-5. Analyzing the center of the weld, it is clear that this specimen is correctly welded. On the retreating side a small interface defect (filled with adhesive) is present. PAUT detected an interface defect on this specimen, but did not indicate that it was correctly welded.

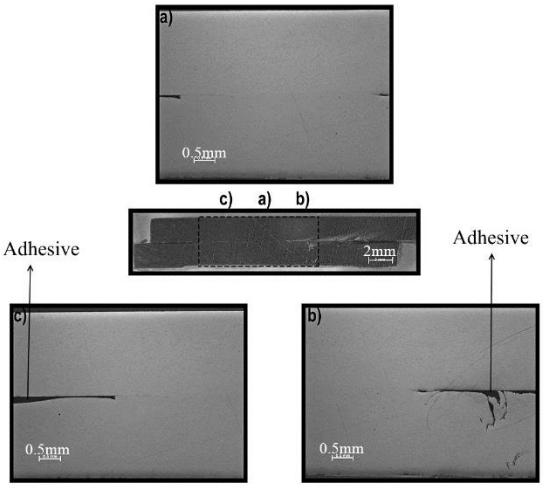


Figure 10 Macroscopic and microscopic figure of the Hyb-5 weld cross sections; a) center of the weld, b) retreating side and c) advancing side.

3.3. Lap Shear Strength Tests

Lap shear strength tests were conducted in order to quantify the joints quality and determine the mechanical strength of the joints. Figure 11 shows the UTS and maximum displacement of the specimens.

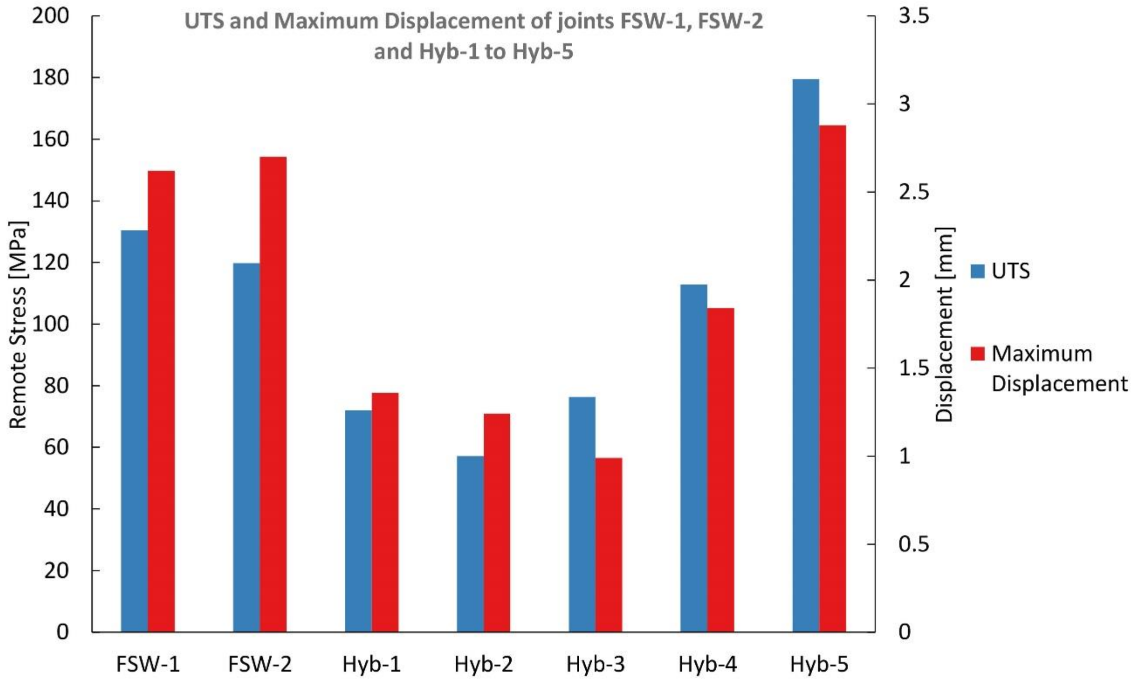


Figure 11 UTS and maximum displacement comparison of every specimen tested.

FSW specimens - FSW-1 and FSW-2 - presented similar results. These specimens showed 45% and 41% of joint efficiency, respectively for FSW-1 and FSW-2. The lap shear tests performed on the hybrid joints showed three different groups of results. The hybrid specimen that presented better mechanical results was Hyb-5, which presented higher UTS and displacement than the FSW only specimens. Hyb-5 specimen showed 62% of joint efficiency when compared with the base material. Specimen Hyb-4 presented UTS similar to FSW-1 and FSW-2 specimens. The remaining specimens - Hyb-1, Hyb-2 and Hyb-3 - showed considerably lower strength than the FSW specimens. Specimen Hyb-2 UTS was 56% lower than FSW-1 and 68% lower than Hyb-5.

3.4. Discussion

Regarding the FSW only specimens, the PAUT results were validated by the microscopy images, both revealed correctly welded joints. The lap shear strength results similar mechanical behavior.

The PAUT results concerning specimens Hyb-1 and Hyb-3, in figure 5, showed a reflection in the middle of the joints thickness. The specimens microscopy, shown in figure 8, revealed the existence of an adhesive layer in the weld zone of the joints, validating the PAUT results. These inspections show that this specimen was very poorly welded, or even non-welded, which is proved by the extremely low mechanical strength presented.

Specimens Hyb-2 and Hyb-4 PAUT results, shown in figure 6, presented a reflection near the back-wall. This reflection is due to a hook defect filled with adhesive created by vertical movement of the material during the FSW process, as the microscopy results, in figure 9, confirm. In both cases the adhesive flow has been created by poor or incomplete FSW process, although in Hyb-4 specimen the material appears to be better stirred. In fact, the production of specimen Hyb-2 used high welding speed, probably leading to the very poorly stirred specimen since the rotating pin stayed a small amount of time in each segment of the joint. Hyb-4 specimen was produced with a more balanced set of FSW parameters, although using a low forging force, the low welding speed used balanced the process leading to a better joint than the Hyb-2 joint, as the lap shear strength tests reveal.

Specimen Hyb-5 also showed a small reflection near the back wall during the PAUT inspection, shown in figure 6. The microscopy analysis showed a small evidence of vertical movement of the material (hook defect) on the retreating side of the weld, however this specimen was correctly welded. This type of defect is a common feature in friction stir lap welding joints and is usual that correctly welded joints present small hook defects. Lap shear strength results prove that this specimen was correctly welded.

PAUT successfully detected non-welded specimens - Hyb-1 and Hyb-3. However using PAUT it was impossible to distinguish specimens with major interface defects (such as Hyb-2 and Hyb-4) from the Hyb-5 specimen which is correctly welded.

4. Conclusions

- PAUT was able to identify correctly welded FSW joints;
- Hybrid joints with major interface defects, either in the middle or in the top of the joint, were identified by PAUT;
- A limitation of the PAUT inspection applied to friction stir weldbonding was found. PAUT wasn't able to distinguish joints with major hook defects on the top of the weld from joints correctly welded with minor hook defects;
- Using PAUT it was possible to realize that the adhesive filled the interface defects;
- Correctly weldbonded specimen - Hyb-5 - presented 38% and 50% higher mechanical strength than FSW-1 and FSW-2, respectively.

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