FRICTION STIR WELDING ON T-JOINTS: RESIDUAL STRESS EVALUATION

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ABSTRACT

The main goal of this work is to characterize the residual stress field in T-joints welded by Friction Stir Welding. The T-joints were composed of two aluminium AA6056 sheets in the flanges and an aluminium AA7075 sheet in the web. The results obtained show that the residual stress field from the transition zone between the thermo-mechanically affected and heat affected zones may be modeled by a logarithmic curve. The maximum tensile stresses obtained were in the order of 100 MPa while the compressive ones reached the value of -40 MPa. Both values were obtained in the flanges as the stresses in the web are much lower than these ones. There are no significant differences between the advancing and retreating sides of the work pieces while between the welding and root ones no conclusions could be effectively made.

1- INTRODUCTION

Friction Stir Welding (FSW) is a welding process that uses a cylindrical shouldered tool with a profiled probe that is rotated and slowly plunged into the joint line between two pieces of sheet or plate material to bring them together using pressure and heat that forms a metallic bond across the interface without actual melting. The advent of Friction Stir Welding (Thomas, Nicholas et al. 1995) allowed a more intense use of aluminium welded pieces and helped the diffusion of this material's alloys to an increasing number of industries. This work tries to contribute to an increase in knowledgement on the residual stress field produced by this welding method in a T-joint.

The relevance of the study concerns the importance of residual stress estimation for the safe performance of structural components. Residual stresses are locked-in stresses which exist in a structural part without the application of any service or other external loads and can arise from production processes. They may be detrimental with a predominant contribution to fatigue and other structural failures (Bussu and Irving 2003).

Therefore, the main goal of this work is to characterize the residual stress field in T-joints welded by Friction Stir Welding. The T-joints were composed of two aluminium

AA6056-T4 sheets in the flanges and an aluminium AA7075-T6 sheet in the web.

2 - WORK PIECE CHARACTERIZATION

2.1 - Shape, dimensions and welding parameters

To characterize the residual stress field two distinct tests were performed, using a different technique in each one: the Sectioning method (Galatolo and Lanciotti 1997) was used in the first one and the Hole Drilling method (ASTM 2008) in the second. Both tests consisted in the characterization of the residual stress field in a friction stir welded T-joint composed of two different types of aluminium alloys: AA6056 and AA7075, subjected to a T4 and a T6 heat treatment respectively and for each method it was used a different work piece. From now on, the flange side where the welding has been executed will be referenced as welding side and the opposite side as root side, as it is shown in Fig 1. The AA7075 element will be named web.

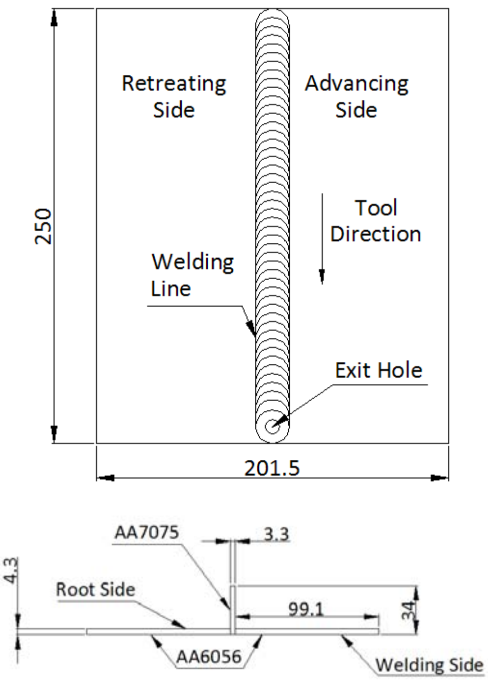


Fig 1 - T-joints welding geometry configuration (dimensions in mm).

The weldment was performed at Instituto Superior Técnico (IST) in Lisbon using an ESAB LEGIO 3UL FSW machine, under vertical downward force control. All the specimens were welded along the plates rolling direction with a planar scrolled (2 spiral striates) shoulder which enabled a null tilt angle. The probe geometry was threaded on a conical body whose diameter ranged from 8 mm (top) to 6 mm (bottom) including 3 vertical helicoidal channels.

The welding parameters were:

- shoulder diameter – 19 mm;
- probe length – 4 mm;
- rotational speed – 1120 rpm (clockwise);
- linear speed – 200 mm/min;
- load – 7000 to 7500 N;
- dwell time – 8 s.

2.2 - Mechanical properties

Table 1 - Mechanical properties of base materials

Material	Source	σ_{YS} [MPa]	σ_{US} [MPa]	ε_s [%]	E [MPa]
AA6056-T4	Experimental Procedure	257.8	352.9	30	77469
AA7075-T6	Literature (Matweb)	503	572	11	71700

2.3 - Metallurgy

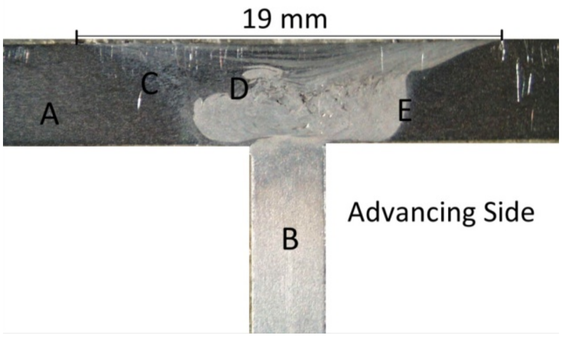
The macro and microstructures of this T-joint are presented in Fig 2. For the chemical etching of the dissimilar joint an 8% concentration of fluoridric acid (HF 8%) was applied. The skin material is AA6056 with the T4 heat treatment (T4 - solution heat treated and naturally aged at 20ºC), and the reinforcement material is AA7075 in the T6 temper (T6 - solution heat treated and artificially aged). In Fig 2a) the macrostructure of the friction stir welded T-joint is presented. Several microstructures were taken in the locations marked in this figure for a more detailed analysis.

As can be seen in the microstructures of locations A and B respectively, Fig 2b) and 2c), the base materials have a completely different microstructure. The AA6056 alloy has larger grains in the order of over 100 µm, all elongated in the rolling direction of the 4.3

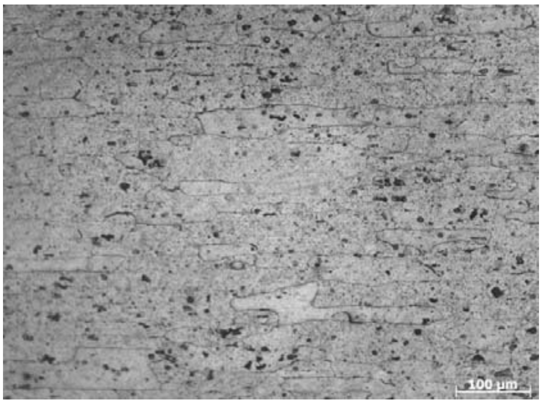
mm thick plate. In the AA7075 alloy, the rolling direction can also be easily recognized, but the grains seem to be smaller.

The FSW process originates transformations in the microstructure. In the nugget zone, the mixture of the two different alloys is easily identified as can be seen in location D, Fig 2e). The nugget zone experiences high strain and is prone to recrystallization. Smaller rounded grains are therefore found in this location with dimensions below 10 µm for the aluminium alloy AA6056. The alloy 7075 also exhibits smaller round grains than the base material.

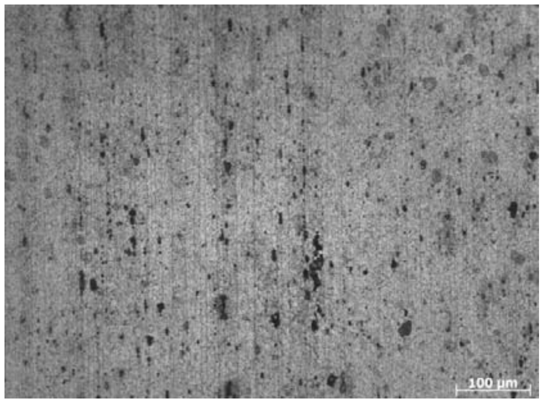
Immediately at the side of the nugget zone is the thermo-mechanically affected zone (TMAZ) which ends at the tool shoulder. In the transition zone C, the change from large longitudinal grains into smaller round grains can be recognized in Fig 2d). In this location and also location E, Fig 2f), on the advancing side of the weld, the material flow inside the weld may be reconstructed by the shape of the elongated grains. A significant vertical flow of the material seems to have taken place during welding.



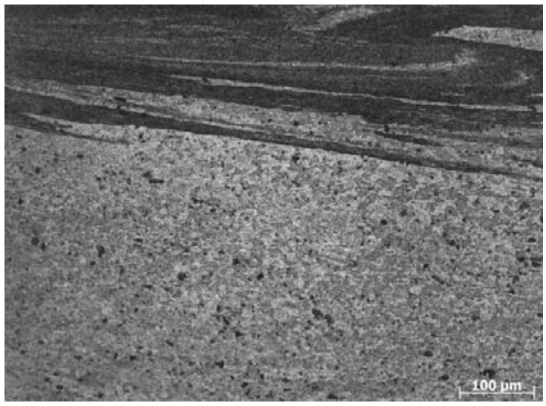
a) Macrostructure of T-joint and microstructures location



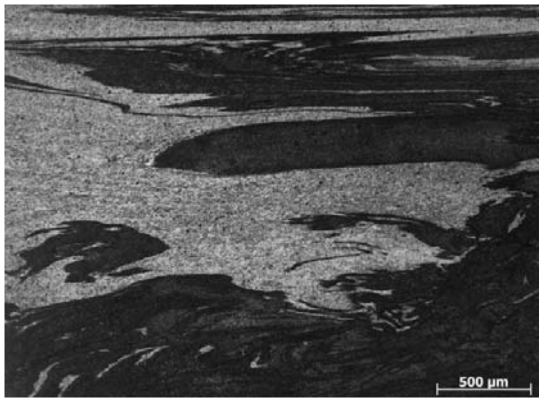
b) A - base material AA6056-T4



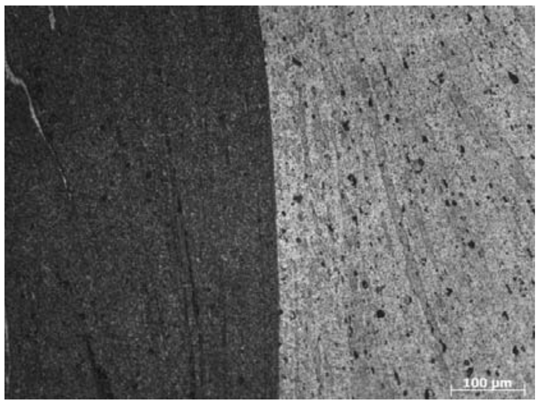
c) B - base material AA7075-T6



d) C – TMAZ/HAZ retreating side transition zone



e) D – Nugget zone



f) E – TMAZ/HAZ advancing side transition zone

Fig 2 - Macro and microstructures of the cross section T-joint 6056-T4+7075-T6.

Outside of the TMAZ, the heat affected zone (HAZ) can be seen for example in the left side of Fig 2d), where larger grains than those of the base material can be found.

2.4 - Hardness profile

This characterization was based in the selection of a cross section of the T that was the mirror of the one used to get the macrostructure. Microhardness points were distanced by approximately 0.3 mm and more dense data acquisition was made in the area of the nugget. They were measured along three horizontal lines in the flanges and other three lines along the web. Fig 3 illustrates the referential used in the measures and marks the zero. The X axis corresponds to one of the lines where data was measured in the flanges while the other were 0.93 mm in the negative direction of the Y axis and 1.05 mm in the positive one. In each one of these lines, data was acquired between -13.2 and 13.2 mm in the X axis. The Y axis also corresponds to one of the measured lines, in this case in the web, while the other two were placed 0.78 mm and -0.79 mm from this line, in each direction of the X axis respectively. In these lines, data was acquired between -16.48 and 1.55 mm in the Y axis. A total of 444 microhardness points were acquired. **Fig 4** show the hardness variation along the different directions of the T joint section.

The difference in hardness of the web and flange of the T is clearly observed, as expected due to the different hardness of base materials. A decrease of the hardness in the TMAZ is shown, whereas the nugget area presents a quite irregular pattern, which can be attributed to the non homogenous mixture of the dissimilar materials.

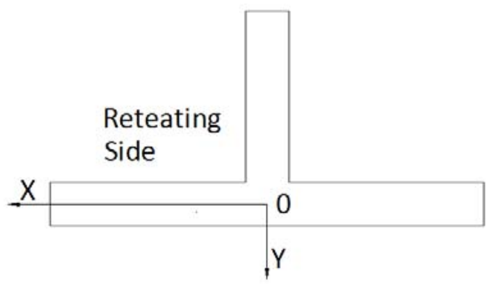


Fig 3 – Microhardness measures' referential.

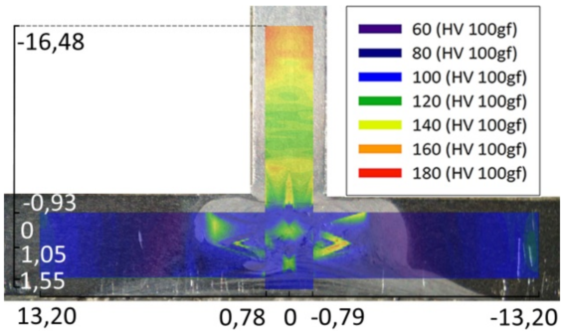


Fig 4 - Hardness variation along the T.

There is no significative difference between the lowest values of hardness on advancing and retreating sides. The hardness in the base material is around 100 HV for AA6056-T4 and 170 HV for AA7075-T6.

In the nugget zone, the microhardness values jump from the AA6056 base material values to the AA7075 base material values depending on where exactly the measurement was made. This happens due to the heterogeneous mix of materials in this region.

After reaching the minimum, hardness tend to base material values as we move from the TMAZ to the HAZ and then to the unaffected zone.

3 - SECTIONING METHOD

3.1 - Experimental procedure

For the acquisition of the longitudinal (weld bead direction) stress, relieved during the cut, twenty four strain gages were used, fig 5. Since no significant difference was expected between the AA6056 plates at the retreating and advancing sides, only four strain gages were placed on the retreating side to verify the results' symmetry. The remaining sixteen strain gages were placed on the advancing side. Three strain gages were bonded in one face of the web and one in the other face. The three gages were bonded in the advancing side.

The work piece was 250 mm in the longitudinal direction and the cut was made right in the middle of it, at 125 mm from each extreme, by a band saw. The gages were placed 10 mm way from the cutting line, in the weldment direction. The reference from which distances were measured was the welding line.

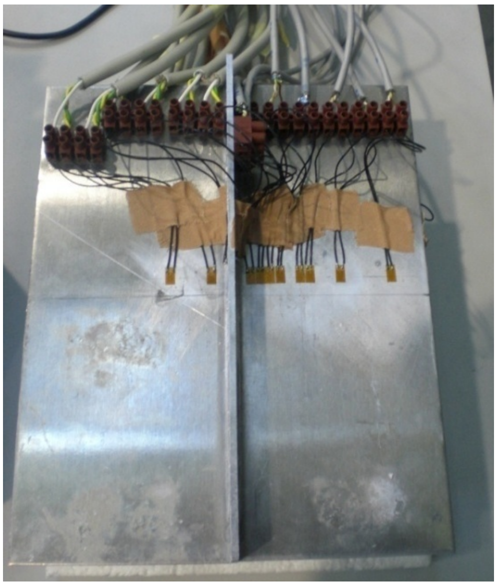


Fig 5 - Instrumented plate before the Sectioning method.

3.2 - Results

The residual stress data obtained with the Sectioning method can be seen from Fig 6 to Fig 9.

It was verified that the stresses in the retreating side of the work piece are not significantly different from those in the advancing side as it was supposed from the beginning, based in previous works (Moreira 2008). In the following analysis it will be used data only from the advancing side.

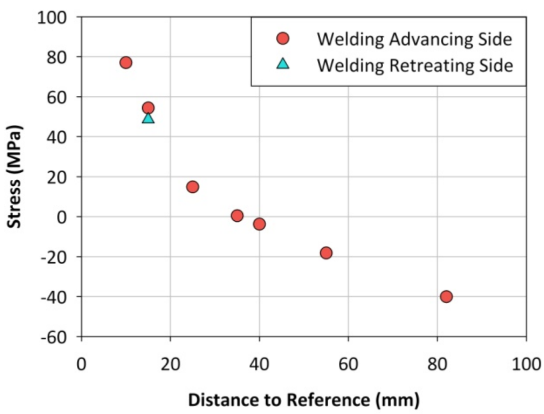


Fig 6 - Welding side stress - Sectioning method.

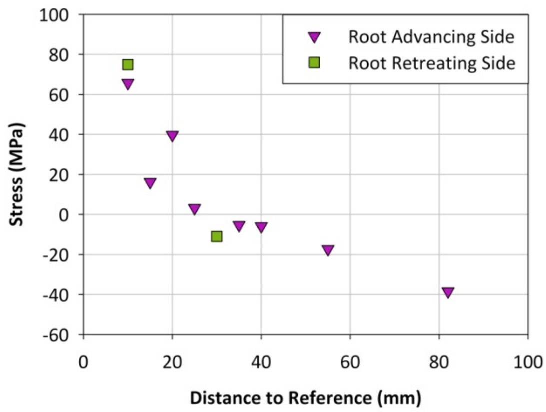


Fig 7 - Root side stress - Sectioning method.

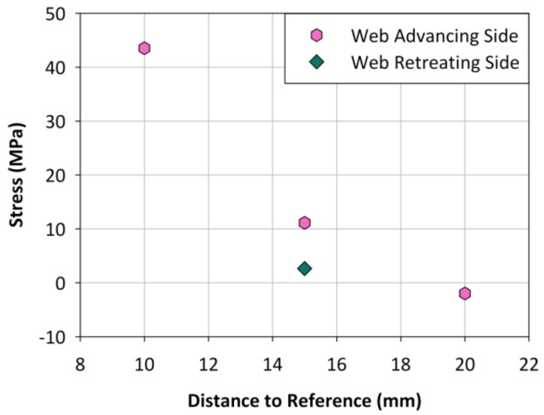


Fig 8 - Web side stress - Sectioning method.

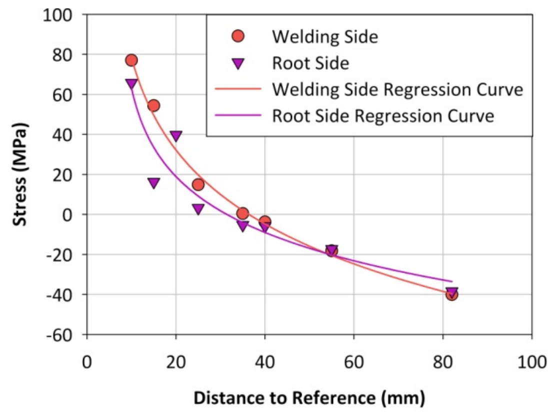


Fig 9 – Welding vs. root side stress - Sectioning method.

It was verified that the stresses in the retreating side of the work piece are not significantly different from those in the advancing side as it was supposed from the beginning, based in previous works (Moreira 2008). In the following analysis it will be used data only from the advancing side.

In the web the residual stress is lower than in the other sheets and it becomes compressive around 20 mm. The maximum tensile stress is lower than 50 MPa.

Comparing the welding side to the root side, there is no significant difference between the values obtained. There is an exception, at 15 mm in the root advancing side. However, this value can be disregarded as it can be taken as a misread of the gage. In both sides the residual stresses become compressive at around 30-40 mm and the gradient becomes less accentuate from this point on. The compressive stress reaches the value of -40 MPa at the end of the points obtained. The maximum stress is lower than 80 MPa.

The expected "M shape" was not observed. This can be due to the joint shape, as M-shape was traditionally obtained from butt joints, or it can also be because the data was obtained in the heat affected and non-affected zones so, in the "outside legs" of the "M". The values obtained at 10 mm from the reference line can be considered in the transition zone between TMAZ and HAZ and can be good estimates of the maximum stress value existing in the work piece.

The data profile obtained suggested that the curves that would better fit the experimental data should be logarithmic because there are high values of stress nearer the welding line and stress becomes compressive as we move away from it. With this in mind, the fitting curves were obtained using a non-linear regression with the curve family:

$$y = y_0 + a \times \ln|x - x_0| \qquad (1)$$

The parameters' estimates are shown in

Table **2**, as well as the percentage of the data variation that can be explained by the respective curve. In spite of the relatively lower value of root side's coefficient of determination (explained by the larger imprecision and dispersion of the experimental data) these values support the idea that in heat affected and non-affected zones the residual stress distribution in T-joints could be modeled by a logarithmic curve. This means that residual stress values decrease as we move away from the welding line with a decreasing speed rate turning itself compressive at some point.

Table 2 – Regression parameters – Sectioning method

Curve	R^2	a	x_0	y_0
Welding side	99%	-45	4	155
Root side	89%	-30	7	95

4 - HOLE DRILLING METHOD

4.1 - Experimental procedure

The data acquisition was performed on 18 different points distributed in root and welding advancing sides, as it can be seen in Fig 10. The orientation and the distance of the strain gage rosettes were chosen in a way that the grid of each one was at least at a 15 mm distance of a hole drilled previously. The reference continues to be the welding line, as it was in the Sectioning method. In the root side, the first eight rosettes centres were aligned along two lines separated by 20 mm while in the welding side all the rosettes were aligned along three lines also separated by 20 mm from each other. In the root side, four experiments had to be withdrawn so two more drills had to be performed in order to

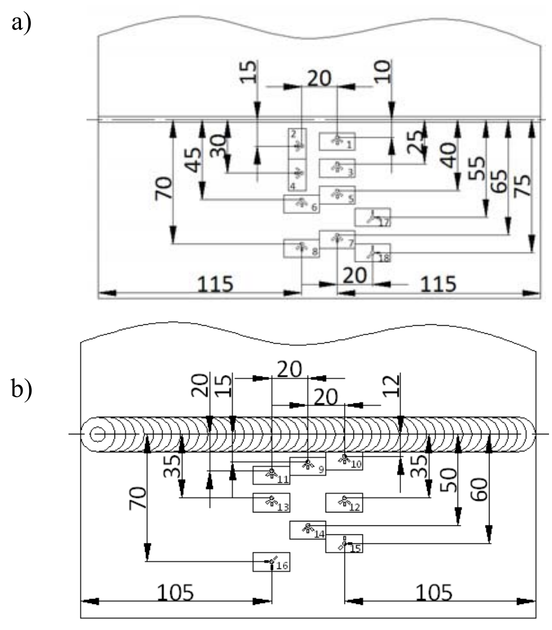


Fig 10 - Strain gage rosettes' positions at: a) root side b) welding side.

accomplish valuable results. The strain gage rosettes were placed at a line 20 mm from the right one and it was named “special”.

To perform the hole it was necessary to centre it with a precision milling guide that was attached to the test part and accurately centred over a drilling target on the rosette.

The drilling was made using a carbide-tipped cutter with 1.6 mm of diameter attached to an air turbine. The experimental setup is shown in Fig 11.

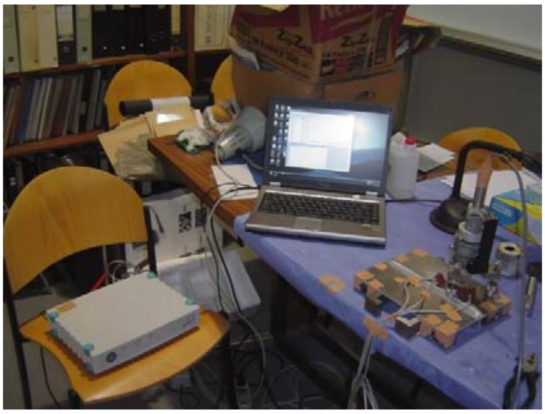


Fig 11 - Experimental setup.

4.2 - Results

The residual stress values presented here were obtained with the help of “H-Drill v3.01 - Hole-Drilling Residual Stress Calculation Program” created by Gary S. Schajer and distributed by Vishay Micro-Measurements. The Integral method was used to calculate the stresses from all the experiments to maintain the calculation uniformity since most of the data was only possible to compute using this method.

The values of the mechanical properties used in the computation of the Hole Drilling results (using the referred software) are shown in Table 3.

Table 3 - Mechanical properties used in computation of the Hole Drilling results

	σ_{YS} [MPa]	ν	E [GPa]
AA6056-T4	257.8	0.3	70

In order to compare the results from the Sectioning method with the ones obtained in the Hole Drilling, it is essential to plot “Stress” *vs.* “Distance to Reference”, for each depth. Because of the excessive approximation that are the measures from the first steps of measurement, the first two calculated series of stress, from 0.033 and 0.15 depths, were disregarded in this analysis. **Fig 12** to Fig 15 show the results obtained.

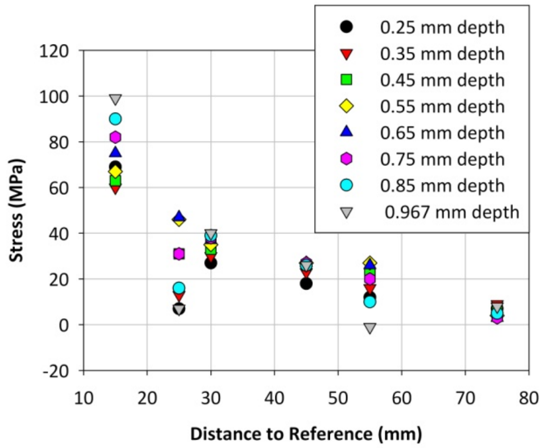


Fig 12 - Hole Drilling results - root side.

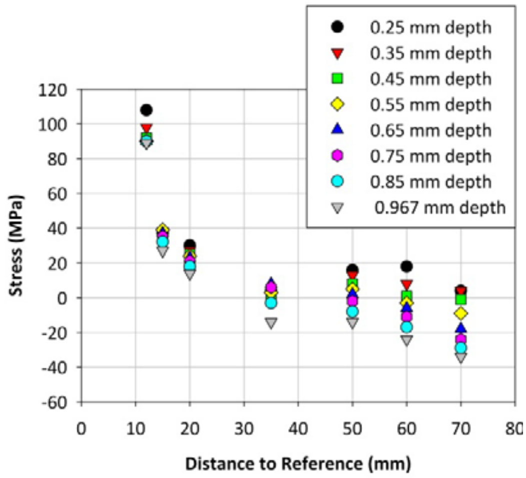


Fig 13 - Hole Drilling results - welding side.

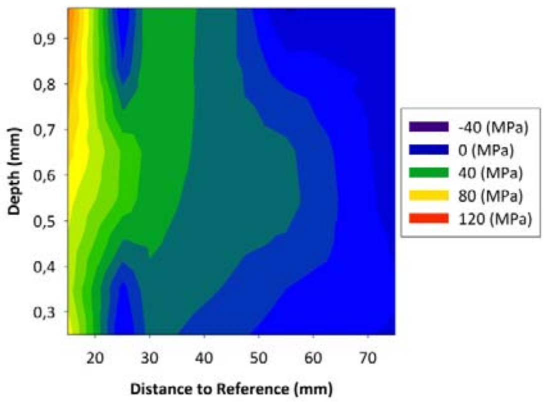


Fig 14 – Hole Drilling results – root side.

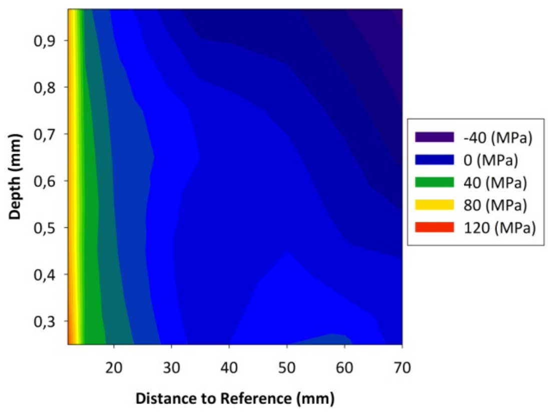


Fig 15 – Hole Drilling results – welding side.

These results show a significant difference between residual stresses in the root and the welding sides. Contrary to the Sectioning method, these results show that the residual stress has higher tensile magnitude in the root side. In this side the stresses do not even become compressive (approximating 0 MPa) as it happens in the welding side (and in the results from Sectioning method) where residual stresses become compressive at around 30 to 40 mm from reference for almost every depth. In the welding side stress becomes compressive between 30 to 60 mm from the welding line and the values can get to the -40 MPa.

In both cases the residual stresses are not higher than 100 MPa (except for the first depth at 12 mm in the welding side) and this value can be an estimate of the maximum tensile stress installed in the work piece as it is near the transition zone between TMAZ and HAZ. As in the Sectioning method, the expected “M shape” was not observed as the data was obtained in the heat affected and non-affected zones therefore in the “outside legs” of the “M”.

As it was made for the Sectioning method, there were obtained regression curves for this data. The comparison between the two methods required the use of the same logarithmic curve family (1):

The curve parameters’ estimates are showed in Table 4 and Table 5 as well as the percentage of the data variation that can be explained by the respective curve.

Table 4 - Regression parameters – Hole Drilling method root side

Curve	R^2	a	x_0	y_0
0.25 mm	90%	-3	15	24
0.35 mm	86%	-4	15	33
0.45 mm	94%	-14	13	69
0.55 mm	95%	-29	5	135
0.65 mm	97%	-28	9	126
0.75 mm	95%	-17	14	79
0.85 mm	90%	-11	15	54
0.967 mm	86%	-8	15	42

Table 5 - Regression parameters – Hole Drilling method welding side

Curve	R^2	a	x_0	y_0
0.25 mm	97%	-10	12	47
0.35 mm	97%	-11	12	49
0.45 mm	98%	-13	12	50
0.55 mm	99%	-15	12	56
0.65 mm	99%	-17	12	58
0.75 mm	98%	-18	12	59
0.85 mm	99%	-19	12	57
0.967 mm	99%	-20	12	52

The results show that the large differences between the two sides start at the depth of 0.45 mm. From this depth on, the differences tend to be larger and they get even larger as we move away from the welding line. This significant difference was not expected according to the results obtained in the Sectioning method.

There are a lot of reasons that can explain the differences and the main ones derive from the proper Hole Drilling method itself and its procedure.

As it can be seen in Tables 4 and 5, the data obtained from root side is more disperse and do not fit in the regression curves as well the data obtained from welding side. The phenomenon does not occur in all depths so the problem is not in the chosen curve family; it is instead in the experimental procedure itself. In the root side we cannot observe any pattern when we move to deeper depths: contrary to the welding side, in the root side stress values do not tend to be lower as well as they do not tend to be higher. This variability is one of the reasons that can explain the lower values of some curves' coefficients of determination. In spite of the values obtained, the curve family used was the one that gave the best results and we can continue to consider that residual stress can be modeled with a logarithmic decaying curve from the transition zone between TMAZ and HAZ to the unaffected material. The stress values decay at slower rates as we move away from the welding line and eventually become compressive.

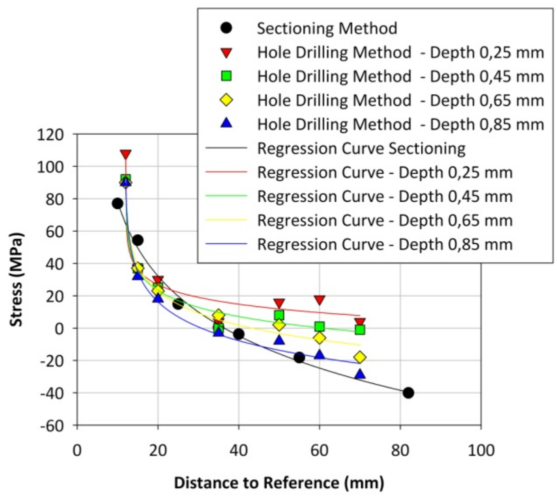


Fig 17 - Comparison Sectioning vs. Hole Drilling methods – welding side

5 - COMPARISON: SECTIONING *VS.* HOLE DRILLING METHODS

For the comparison between the two methods there were analyzed the two different sides of the work pieces. The results from the Sectioning method displayed no significant differences between the advancing and retreating sides so the results only refer to the advancing one. From the Hole Drilling method there are only four depths represented not to turn the graphics unreadable. Fig 16 and Fig 17 show the summary of results obtained.

For both experiments and in both sides of the work piece the trend is similar: the maximum value of residual stress, about 100 MPa, is obtained near 10 mm from the welding line (the transition zone between TMAZ and HAZ) and from then on, the stress value decays at a decaying rate, resembling the properties of a logarithmic curve. For all cases this curve was fitted with success.

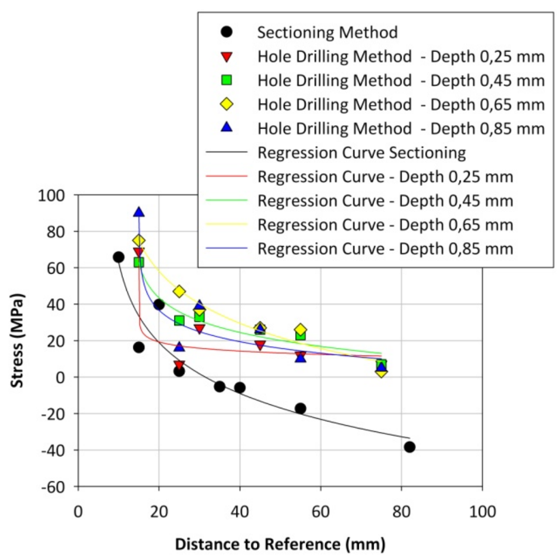


Fig 16 – Comparison Sectioning vs. Hole Drilling methods – root side

The results from the Sectioning and the Hole Drilling methods for the welding side are very similar until 40 mm from the welding line where they start to diverge a little. Until 40 mm, the Sectioning method curve resembles a mean curve to all the depths considered in Fig 17. From this figure, we can conclude that in the welding side, residual stress becomes compressive at around 30 to 60 mm from the welding line. The higher rate at which the Sectioning curve gets to compressive values, relative to the Hole Drilling ones, can be explained by the different specimens used in each experiences.

In the root side, the results differ substantially. The values obtained from Hole Drilling method are significantly higher than those obtained from the Sectioning one and in the first ones residual stress decay without turning compressive, at least until 75 mm from the welding line, the limit of the experience. The decaying speed is also much higher in the results obtained from the Sectioning method. As the Sectioning method curve in this side is very similar to the one at the welding side and the Hole Drilling curves are very similar to this one until 40 mm from the welding line, the reasons to this difference could be the same as the ones between different sides of the Hole Drilling experiment. For this side nothing can be concluded about the point where residual stress becomes compressive (if it really becomes) but we can still accept the logarithmic model to its behavior and the maximum value of stress at around 100 MPa.

6- CONCLUSIONS AND FUTURE WORK

From the results obtained from the experiments in T-joints of AA6056 and AA7075 welded by Friction Stir Welding we can conclude that the maximum residual stress value is around 100 MPa, it is tensile and occurs in the flanges, in the transition zone between the thermo-mechanically affected and heat affected zones. In the web the residual stress is tensile and less than 50 MPa (at least from 10 mm on after the welding line).

The residual stress field, from the transition zone referred in the last paragraph on, can be modeled by a logarithmic curve: residual stress values decay at a decaying rate as we move away from the welding line, becoming compressive at a certain point.

There is no significant difference between residual stresses in the advancing and retreating sides of the T-joints studied. Residual stress in the flanges came similar to both welding and root sides in the Sectioning method but went significantly different in the Hole Drilling one.

Both methods utilized gave the same results for the welding side of the joints which enables the conclusion that in this side of the T-joint residual stress becomes compressive around 30 to 60 mm away from the welding line, reaching -40 MPa.

In the root side nothing can be clearly concluded, besides the logarithmic trend of the stress, as the results from each experience differ. The main reason for the discrepancy can be the difference between the weldments of the two T-joints. Another reason can be experimental errors that were not detected during and after the experiences.

To understand the significant differences between welding and root sides occurred in the Hole Drilling method it is necessary to perform more tests. The next step in this work should focus primarily on understanding this phenomenon by running the same Hole Drilling test in another T-joint similar to the ones used in this work. The current T-joints available are no longer suitable for this job and the work piece used should be longer, allowing the execution of Hole Drilling and Sectioning methods in it, because residual stress is believed to be approximately constant in the welding direction. In this test, along with the root side, it should be also tested the welding one, only by one of the methods, to confirm the results here presented.

7- ACKNOWLEDGMENTS

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