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RESIDUAL STRESSES IN ALUMINUM ALLOY AA7475-T761 USING X-RAY DIFFRACTION TECHNIQUE

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Abstract. *Friction stir welding (FSW) is a well-known solid-state welding technology invented in 1991 at The Welding Institute (TWI), in England. As a solid-state process, it is expected low temperature (below the melting point) as well as low distortion after welding. Therefore, low distortion involves low residual stresses, and that is the best condition when designing components subjected to cyclic loads and fatigue. Using X-Ray diffraction technique to analyze residual stress, this study proposes to evaluate the results on a similar butt welded joint of AA7475-T761 aluminum alloy sheet with 1.6 mm thickness. Rotational speed, probe plunge depth, and tool tilt were kept constant whereas tool travel speed was varied. All joining were made in an FSW dedicated machine, model GG-7 manufactured by MTI available at IPT-LEL. The results are consistent with literature data and in terms of the mechanical design of components. Longitudinal residual stresses values are approximately 11% of tensile strength and 13% of yield strength.*

Keywords: *FSW, Residual stress, Design of experiments (DOE), Aluminum*

1. INTRODUCTION

Friction stir welding (FSW) is a solid-state joining technique and its lack of melt between parent material and a filler metal guarantee better joint properties, dimensional stability and repeatability (Mishra and Ma, 2005). This process is usually applied to join aluminum alloys but is also applicable to steels, titanium alloys, as well as nickel-based superalloys (Mishra and Ma, 2005). Typical examples of FSW applications are the manufacturing of rocket-fuel tanks by Boeing, the production of the civil aircraft Eclipse 500, the construction of a catamaran using extruded and friction welded profiles and the manufacturing of automobiles structures such as bumper beams, rear spoilers and alloy wheels (Shah and Tosunoglu, 2012). Residual stresses are intrinsic to almost all manufacturing processes that involve deformation, heat treatment, machining, and sometimes in casting parts. Therefore, they are considered to represent a system of self-balancing efforts from any mechanical manufacturing system.

Thermal-mechanical effects, as well as microstructural transformation, can be regarded as the main mechanisms for introduction of residual stresses in the FSW process. According to Williams and Steuwer (2010) along of the weld there is an extensive compressive area due to thermal expansion of heat and expanded material, being restricted by surrounding cold material, as shown in Fig. 1. Thus, the plastic strain will occur where the stress exceeds the compressive yield strength. On the back of the weld there is the opposite effect: a region of tensile stresses due to contraction of surrounding cold material, where plastic deformation will occur if stress exceeds the compressive yield strength. Williams and Steuwer (2010) also highlight the reason why tensile residual stress principally arises. It's not only due to shrinkage forces on cooling as is commonly stated, but also due to plastic compressive flow on heating. Additionally, if there is no plastic compressive flow then there will be no tensile residual stress.

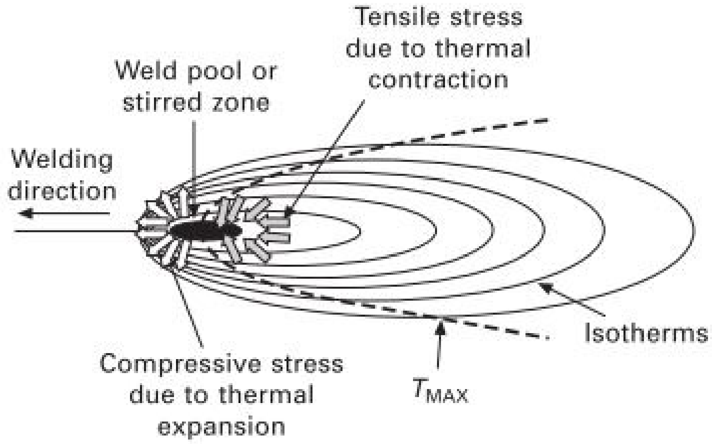

Figure 1. Temperature and stress field around welding process (Williams and Steuwer, 2010)

High tensile residual stresses have a harmful effect on the material regarding life in fatigue and corrosion. According to Kumar et al. (2013), FSW introduces high-tensile stresses when applied in aluminum alloys of 2xxx and 7xxx series because they have high yield strength values. Zapata et al. (2016) observed maximum values of approximately 52 MPa on the retreating side when joining aluminum alloys AA2024 using FSW at 500 rpm and 45 mm/min. Gachi et al. (2011) found residual stresses values close to 120 MPa when joining alloys AA7075-T6 at a rotational speed of 2000 rpm and tool travel speed of 25 mm/min.

There are many techniques to obtain residual stresses values, and they are divided into destructive and non-destructive. As destructive techniques, it's possible to cite blind hole drilling, hole drilling, crack compliance, among others. However, their main disadvantage compared to non-destructive techniques lies in the necessity of mechanical intervention on the specimens, giving only one possibility of measurement. The non-destructive technique lies on the possibility of measurements replication as few times as necessary without loose of information, and some of them are X-ray diffraction, neutron diffraction, synchrotron x-ray, but not limited to those. In this research, X-ray diffraction technique was chosen.

As residual stress is an extrinsic property and X-ray diffraction technique capability is to measure intrinsic properties, e.g. strain, then residual stress is always calculated not measured. The strain is measured in the crystal lattice, and, linear elastic distortion is assumed. This technique is based on Bragg's law and occurs at 2θ angle, expressed by the Eq. (1), where "n" is an integer and denotes the order or diffraction, "λ" is the X-ray wavelength, "d" is the lattice spacing of crystal planes, and θ is the diffraction angle.

$$n \cdot \lambda = 2 \cdot d \cdot \sin\theta \qquad (1)$$

Structures with the presence of tensile residual stress have its Poisson's coefficient contracted, reducing the lattice space and increasing slightly the diffraction angle 2θ. Through the most common method of measurement, $\sin^2\psi$, plane stress state is assumed in the surface and multiple angles ψ are measured, multiple points are obtained, and a straight line is adjusted by least square regression. Residual stress value is obtained through the slope of this straight line (Prevéy, 1986a).

The objective of the present research was to evaluate the characteristics of a joint made of similar materials, joined by friction stir welding (FSW), under the perspective of the residual stresses compared to tensile and yield strength using X-ray diffraction technique.

2. EXPERIMENTAL PROCEDURE

2.1 Specimen

This research used sheets with 1.6 mm nominal thickness of the aluminum alloy AA7475, heat treated according to T761 temper, i.e., solubilized, rapidly cooled and artificially aged. Specimens used in this research were cut to 200 mm length and 100 mm width. Table 1 shows typical values for chemical composition and Table 2 for mechanical properties (The Aluminum Association Inc., 2006).

Table 1. AA7475-T761 chemical composition

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others		Al Min.
									Each	Total	
AA7475-T761	0.10	0.12	1.2-1.9	0.06	1.9-2.6	0.18-0.25	5.2-6.2	0.06	0.05	0.15	Rem.

Table 2. AA7475-T761 mechanical properties

	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Young's module (GPa)
AA7475-T761	517	448	12	70.3

2.2 Tool

The tool used for butt joining consisted of an integrated one-piece conical smooth probe and a concave smooth shoulder. Tool material was AISI H13, double tempered (first at 510 °C and second at 600 °C) to attain required microstructure and a hardness of approximately 46 HRC. Also, in order to improve probe and shoulder surface wearing resistance, it was nitride as represented in Fig. 2.

Figure 2. FSW tool after nitriding

2.3 Joint equipment

The rotational speed was 1450 rpm, probe plunge depth was 0.1 mm and tool tilt was 2°. Tool travel speed was 40 mm/min (run 27) and 90 mm/min (run 28). All joining was carried out at the Lightweight Structures Laboratory (LEL) of the Technological Research Institute (IPT), located in the São José dos Campos' Technological Park, State of São Paulo. The equipment used to join the specimens was manufactured by the American company MTI, model GG-7 (Fig. 3), equipped with a Computer Numerical Control (CNC) interface, a 3800 x 3900 mm table, 80 kN maximum axial (forging) force, 3000 rpm maximum rotational speed, 3000 mm/min maximum tool travel speed and 280 N.m maximum torque.

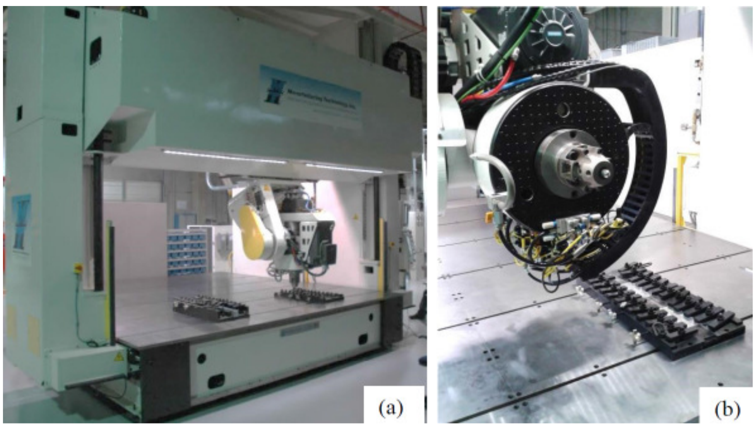

Figure 3. FSW dedicated equipment model GG-7: (a) General view; (b) Machine detail

2.4 Residual stress equipment

Residual stresses were measured with X-ray diffractometer model Xstress 3000 G2R (Fig. 4), manufactured by Stresstech. Diffraction was obtained by the d-$\sin^2\chi$ measurement mode. This equipment uses chromium (Cr) X-ray tube, with a voltage ranging from 5 to 30 kV and current from 0 to 10 mA. The voltage was configured to 30 kV and current to 9 mA. The χ (chi) angle was settled between -45 to 45°. Detectors are MOS position sensitive type and symmetrically positioned. They were positioned manually at a diffraction angle 2θ of 139.1°, compatible to aluminum structures. A collimator of 2 millimeters was chosen. All residual stresses measurements were made 14 months after joining the specimens, due to an intrinsic characteristic of natural aging of aluminum alloy AA7475, thus eliminating this variable, similarly to Buglioni et al. (2015). The residual stresses measurements were carried out only a few micrometers underneath the surface, resulting in a sensitivity measurement and surface-dependent. Thus, no surface preparation was executed, avoiding any interference on joining surface after-joining condition (Prevéy, 1986b). A total of thirteen points were measured, which one point was in the centerline of the join, six points to the advancing side and other six to the retreating side. These six points were divided into two segments: four points with 2 mm distance between each other and last two points were at 50 and 60 mm far from the centerline of the join. Data were acquired and processed in the Stresstech proprietary software named XTronic.

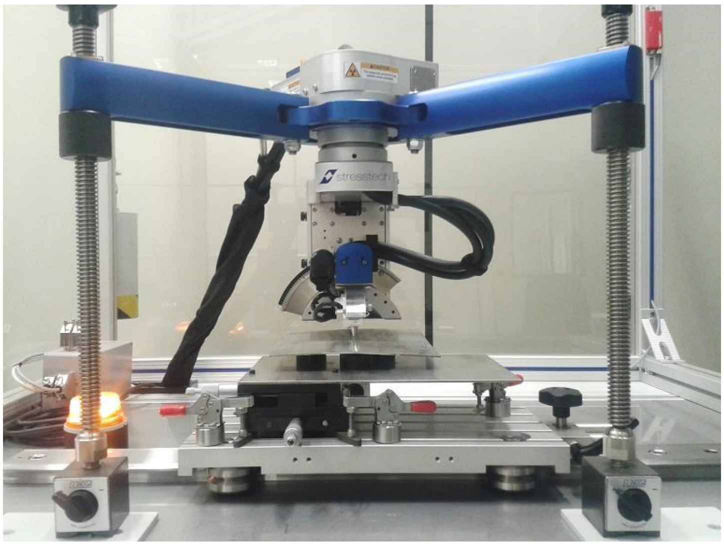

Figure 4. X-Ray diffractometer Xstress 3000 G2R

3. RESULTS AND DISCUSSIONS

3.1 Specimens after joining

After welding the specimens, appropriated marking was done prior to subsequent analysis. A visual inspection was done on the joint area evaluating its final state. It was observed if there was the presence of excessive flash, any superficial defect or flaw, and also surface finishing aspect. Figure 5 shows both runs analyzed in this research. Run 27 presented a good surface finishing aspect, as well as run 28, without any superficial defect or flaw. Just considering the presence of flash, run 28 presented almost none flash after welding, whereas run 27 presented more flash on the retreating side. Nevertheless, this excess of flash didn't compromise residual stresses measurements because they were easily removed without any mechanical intervention using any tools or brushes.

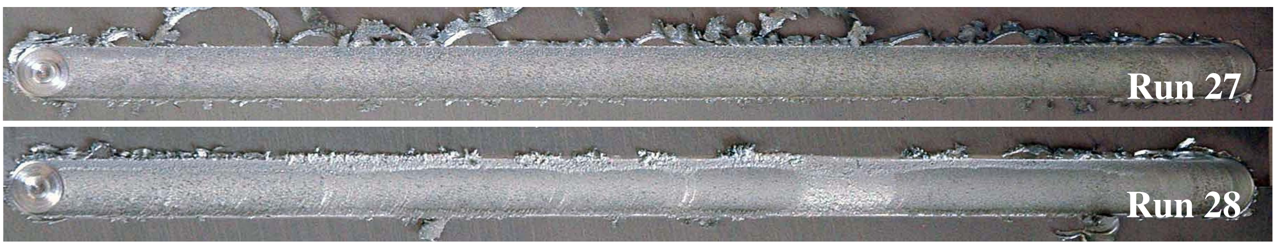

Figure 5. FSW joined specimens, run27 and run 28 respectively

3.2 Residual stresses

Results from residual stresses measurements for aluminum alloy AA7475-T761 are presented in Fig. 6. They were measured in the longitudinal direction and over the upper surface of the weld bead. Run 27 had its maximum value 6 mm far from the centerline of the joint, with 57 ± 12 MPa, while run 28 had its maximum at 4 mm and with 33 ± 9 MPa. Thus, close to the joint, it is possible to note positive values (tensile stress) and far from the joint, negative (compressive stress). The negative values are coherent and related to the sheet metal rolling process, responsible for the insertion of compressive residual stress during manufacturing of the material. It is also noticeable that higher values of tensile longitudinal residual stresses are on the advancing side of the joint, confirming results published by Altenkirch et al. (2009), Deplus et al. (2011) and Dada and Cornish (2013). Comparing the maximum residual stress value found to mechanical properties presented in Tab. 2 they represent 11% of tensile strength and 13% of yield strength. It is noticeable lower values when compared to mechanical properties, identifying this process window parameters as interesting for parts manufacturing by the industry.

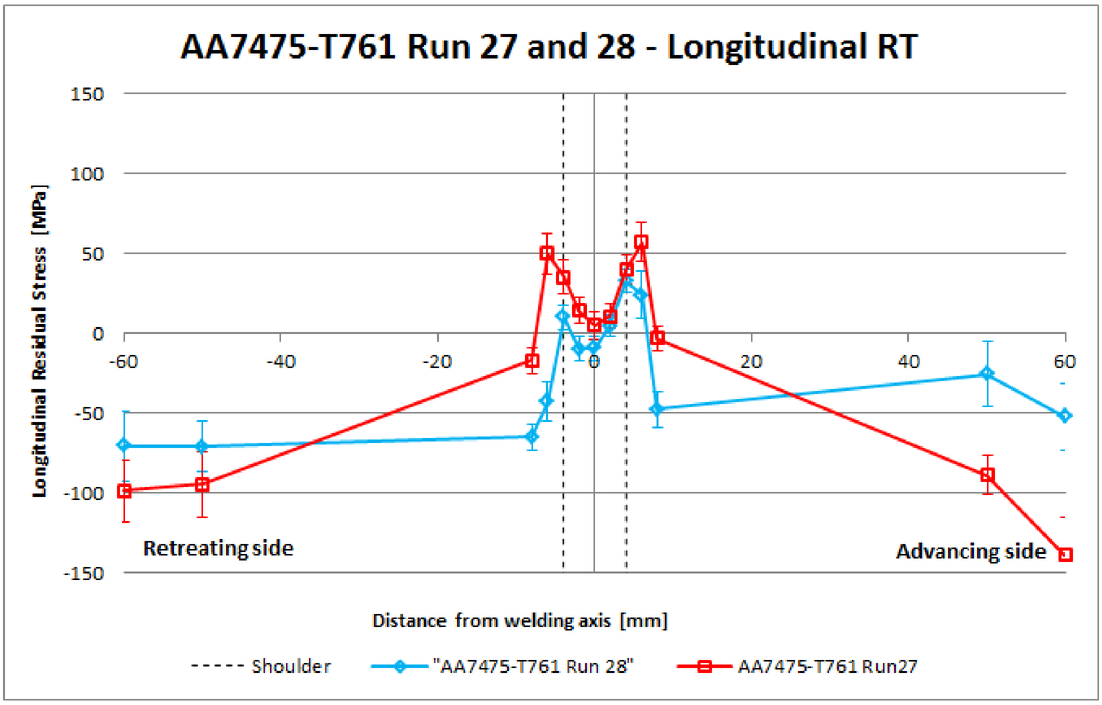

Figure 6. Longitudinal residual stresses in aluminum alloy AA7475-T761

As stated by Williams and Steuwer (2010), due to intense plastic deformation, residual stresses are inherent to FSW joining process. Thus, the magnitude of residual stresses values has its dependency on process parameters, i.e. tool speed and welding speed. Vilaça and Thomas (2011) evaluated the concept known as weld pitch ratio, which is the relationship between rotational speed and tool travel speed. They defined, after several experiments, cold weld classification for weld pitch ratio lower than 2 and hot weld for ratio higher than 4. Extrapolating this concept to this research, considering upper and lower limits, thus higher weld pitch ratio as hot weld (run 27) and lower as cold (run 28), as shown in Tab. 3, it was expected that cold welds had higher residual stresses than hot welds due to increase in tool travel speed as observed by Dada and Cornish (2013) and Buglioni et al. (2015). But it was observed the opposite. This opposite behavior can be attributed to the narrower parameter window defined for this research, which will lead to only hot welds classification according to Vilaça and Thomas definition of weld pitch ratio. Therefore, differences found in residual stress value on each run can be considered irrelevant, because in a macro view of the process it is possible to infer that hot welds will result in a lower tensile residual stresses field due to lower tool travel speeds.

Table 3. AA7475-T761 experimental results

	Run	Rotational speed (rpm)	Tool travel speed (mm/min)	Weld pitch ratio (rev/mm)	Maximum longitudinal residual stresses(MPa)
AA7475-T761	27	1400	40	35.0	57 ± 12
	28	1400	90	15.6	33 ± 9

A profile similar to the letter "M" was obtained, as shown in Fig. 6, very typical of this process as presented by Altenkirch et al. (2009). Vector force analysis can explain the reason why this profile is obtained. In the vector field, there are resultant forces from rotational speed and tool travel speed action. At the advancing side, vectors of resultant forces from rotational and tool travel speed have the same direction, whereas at the retreating side they have opposite directions. Therefore, at the advancing side resultant forces will be added, while at the retreating side they will be subtracted, that results in a higher force intensity applied at advancing side, reason why residual stresses values are higher. Still in forces analysis, close to the center of the joint, its noticeable a decrease in residual stresses values. This phenomenon is attributed to virtually zero resultant force from rotational speed action, in other words, only resultant forces from tool travel speed action will be present, in lower magnitude when compared to both advancing and retreating side, resulting in a lower residual stress value in the centerline of the joint.

4. CONCLUSIONS

The parameters used in this research generated joints with good visual aspects and without any noticed flaw or surface defect. The material selected for the tool was appropriated due to no register of breaking during the experiment or even wear after all joints were made.

The residual stresses maximum values are relatively lower when compared to other studies and also lower to tensile and yield strength, given an opportunity to use these welding parameters window into production welding. Also, lower values of residual stress found are probably related to lower tool travel speed and narrow parameter window. Compressive values of residual stress were observed at the periphery of the joint, consistently to the sheet metal rolling manufacturing process. Specifically in the joint, higher values on advancing side were noted due to the same direction of resultant forces in a vectorial field of forces generated by rotational speed and travel speed, while for retreating side they are opposite direction, generating the "M" profile curve as presented before.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE