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RESIDUAL STRESS EVALUATION OF AA2024-T3 FRICTION STIR WELDED JOINTS

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Abstract. *The main aim of this study was to evaluate the residual stress field in friction stir welded joints of 2024-T3 aluminium alloy using the crack (or cut) compliance method. It is based on the fact that when a cut, simulating a growing crack, is incrementally introduced into a part, residual stresses are relieved on the slot surfaces created, causing the part to deform. Such deformation can be measured by strain gauges attached to specific regions of the part and the residual stress profile that originally existed can be evaluated. Cuts were introduced by wire electro discharge machining (WEDM), in finishing mode, either perpendicularly or longitudinally to the weld nugget, in a 3.2x60x120mm3 rectangular testpieces. For the longitudinal cut testpieces, the slot was introduced in two different positions: on the centre of the weld nugget and 5mm distant from the weld centre line, representing the thermomechanically/heat affected zone. The residual stress intensity factor, Kr, was calculated using a fracture mechanics approach and the inverse weight function method was employed to obtain the initial residual stress profile. Additionally, the residual stress redistribution profiles ahead of the slot were determined for several slot lengths, simulating the growth of a crack into the residual stress field. The results obtained represent valuable information if a damage tolerant design is applied to friction stir welded joints.*

Keywords*: crack compliance method, residual stress, machining, WEDM, saw cut*

1. Introduction

In recent years, friction stir welding has been considered as potential candidate to replace conventional riveting operations in aircraft manufacture. However, it is well known that residual stresses are present in welded structures after fabrication. These residual stresses are likely to affect mechanical and corrosion properties of the materials and therefore to influence the in-service performance of structural components. The effects of residual stresses on the fatigue crack propagation have been reported by several authors such as Itoh et al (1989), Bussu and Irving (2003), Milan and Bowen (2002), Milan and Bowen (2003). Tensile residual stresses increase the crack growth rate by an increase in the effective stress ratio. On the other hand, compressive residual stresses reduce the fatigue crack growth rate by decreasing the stress intensity factor range and/or stress ratio. Additionally, residual stresses were found to affect initiation fracture toughness values of aluminum alloys (Milan and Bowen, 2004a and Milan and Bowen, 2004b).

The main aim of this paper was to measure the residual stresses in AA2024-T3 friction stir welded joints, both longitudinally and perpendicularly to the welding line, using the crack compliance method. Additionally, residual stress redistribution profiles ahead of a hypothetical crack were determined for several crack lengths, simulating the growth of a crack into the residual stress field. The results obtained represent valuable information for understanding fatigue and fracture toughness properties of friction stir welded alloys if a damage tolerant design is employed.

2. The crack compliance method

The crack or cut compliance method is a powerful and easy to implement technique employed to determine both near surface and through the thickness residual stress profiles. It is based on the fact that when a cut, simulating a crack, is incrementally introduced into a part, the residual stresses are relieved on the slot surfaces created, causing the part to deform. Such deformation can be measured by strain gauges attached to specific regions of the part (Fig. 1) and the residual stress profile that originally existed can be evaluated (Prime, 1999).

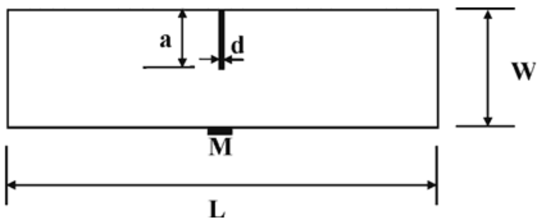

Figure 1. Rectangular plate containing a cut along its center plane, strain measurement taken at the point M.

Assuming a narrow slot (d<<a), linear elastic fracture mechanics equations can be employed to establish a relationship between the measured strains, ε, and the corresponding residual stress intensity factor, K_r (Schindler, 1995):

$$K_{Ir}(a) = \frac{E'}{Z(a)} \frac{d\varepsilon_M}{da} \tag{1}$$

where ε_M is the measured strain at point M during the cutting procedure, a is the slot length, E′ is the generalized form of the Young′s modulus (E′=E for plane stress and E′=E/(1-υ^2) for plane strain) and Z(a) is the "influence function" which depends on the testpiece geometry, cut plane location and strain measurement position, but it is independent on the residual stress profile.

For a rectangular plate, where L>2W, and taking strain measurements at the back face point M, Z(a) is given as (Schindler and Bertschinger, 1997):

for a/W<0.2

$$Z(a) = \frac{-2.532}{(W-a)^{1.5}} \sqrt{1-25.\left(\frac{a}{W}-0.2\right)^2}.\left[5.926.\left(0.2-\frac{a}{W}\right)^2 - 0.288.\left(0.2-\frac{a}{W}\right)+1\right] \tag{2}$$

for 0.2<a/W<1

$$Z(a) = \frac{-2.532}{(W-a)^{1.5}} \tag{3}$$

$K_{Ir}(a)$ and the normal residual stresses, *$\sigma_r(x)$*, that existed prior to the cutting (where the x axis is coincident with the cut plane) can be correlated by the following expression:

$$K_{Ir}(a) = \int_{a_o}^{a} h(x,a).\sigma_r(x).dx \tag{4}$$

where *h(x,a)* is the weight function, which is available for several geometries (Fett and Munz, 1997). In particular, for a single edge crack in a finite width rectangular plate, the weight function is given as:

$$h(x,a) = \sqrt{\frac{2}{\pi a}} \frac{1}{\sqrt{1-x/a}} \left[1 + \frac{1}{(1-a/W)^{3/2}} \sum_{\upsilon,\mu} A_{\upsilon,\mu} (a/W)^{\mu} (1-x/a)^{\upsilon+1}\right] \tag{5}$$

where $A_{v,\mu}$ values are found in Table 1.

Table 1.Weight function coefficients for rectangular testpieces (Fett and Munz, 1997).

ν	μ =0	μ = 1	μ = 2	μ = 3	μ = 4
0	0.4980	2.4463	0.0700	1.3187	-3.067
1	0.5416	-5.0806	24.3447	-32.7208	18.1214
2	-0.19277	2.55863	-12.6415	19.7630	-10.986

Knowledge of $K_{Ir}(a)$ profile (obtained by Eq. (1)) makes possible to calculate $\sigma_r(x)$ profile through the inversion of Eq. (4). One of the methods used for such purpose is the incremental stress method (Schindler 1995), where the stress profile is approximated by a series of small steps as depicted schematically in Fig. 2. The stress level in each step can be calculated by applying Eq. (4) to a hypothetical, incrementally prolonging crack. This leads to a discrete form of Eq. (4):

$$K_{Ir}(a_i) = \sum_{j=1}^{i} \sigma_j \int_{a_{j-1}}^{a_j} h(x, a_i)dx \qquad (6)$$

Using Eq. (6) sequentially allows each σ_j to be determined and the stress profile can be determined. The resulting stress distribution converges to the exact solution $\sigma_r(x)$ as $\Delta a \rightarrow 0$.

The procedure described above is able not only to determine the initial residual stress profile that was present in the material before the slot was introduced, but also the redistributing stress profiles ahead of the slot tip, by simply changing the integration limits in Eq. (6).

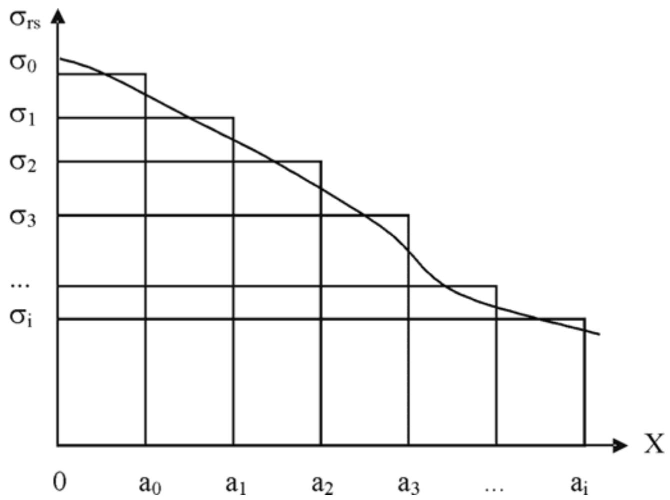

Figure 2. Stress profile approximation using small constant stress steps.

3. Experimental procedures

Plates of AA2024-T3, 3.2mm thick were friction stir welded along the rolling direction. Mechanical properties of the material are provided in Table 2. Welding parameters are confidential to the manufacturer, EMBRAER. Then, $60x120mm^2$ rectangular testpieces were machined by wire electro discharge machining in two different configurations, as represented in Figure 3.

Table 2. Mechanical properties of AA2024-T3 alloy.

Material	UTS (MPa)	σ_y (MPa)	e (%)	RA (%)	E (GPa)
2024-T3 Transverse	459.3	302.9	21.5	24.5	83.3
	465.4	311.7	21.1	23.0	81.3
	466.0	307.8	21.7	21.6	78.7
Average	463.6	307.5	21.4	23.0	81.1
2024-T3 Longitudinal	473.6	355.7	21.2	18.7	83.8
	481.6	351.2	21.4	20.2	77,9
	475.5	344.0	20.7	23.5	75.2
Average	476.9	350.3	21.1	20.8	79.0

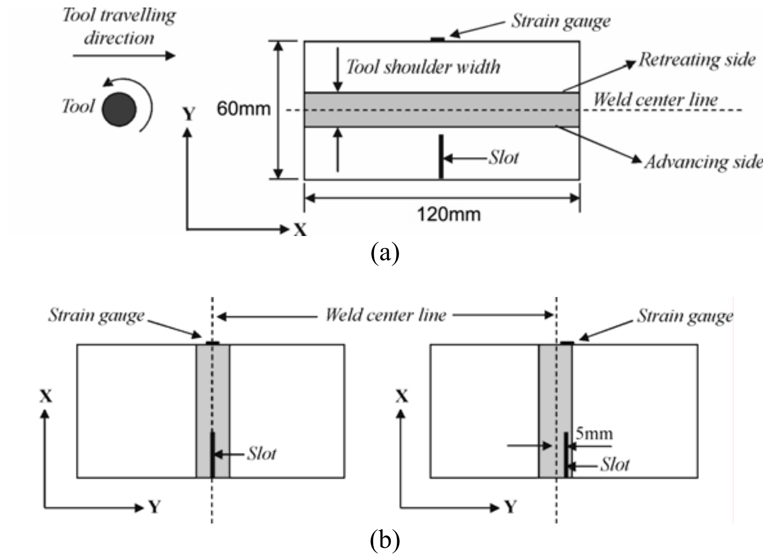

Figure 3. Testpiece configurations: (a) Transverse testpiece for measuring longitudinal stresses; (b) longitudinal testpiece for measuring transverse stresses, slot at 0mm (left) and 5mm from the weld center line. Testpieces presented in (b) present the same dimensions as in (a).

A strain gauge was glued to the back face of each testpiece, in a configuration similar to the one presented in Fig. 3. A plastic resin was applied on top of the strain gauge and wires to avoid contact with the environment. Shielded wires were used to connect the strain gauges to the strain data acquisition apparatus in order to minimize electromagnetic interferences.

Cutting was performed by WEDM either longitudinally or perpendicularly to the weld line. As depicted in Fig. 3b, for longitudinal testpieces, the slot was introduced in two different positions: 0mm e 5mm distant from the nugget center line (on the advancing side of the weld), to simulate a crack growing in the weld and in the heat affected zone, respectively. For perpendicular testpieces the slot approached the nugget from the advancing side of the rotating FSW tool. Recent work performed by Milan et al (2005) has found that WEDM is the best choice for introducing the slot because it is more practical and precise and it is less likely to introduce additional stresses. For all tests, increments of 0.5mm were chosen for each step and the readings were taken 5min after the slotting procedure in each step had finished.

After the strain data were obtained as a function of the slot length, the secant method was used to calculate $d\varepsilon/da$ values which were employed in Eq. (1). After K_r values were found, the residual stress profile was determined by the incremental stress method, using a routine created in Mathcad software. Residual stress redistribution profiles were determined using the same procedure as described above, but changing the initial slot length in the calculations.

4. Results and discussions

4.1 Transverse slot testpieces

Figure 4 shows longitudinal residual stress intensity factor profile, K_{rx} calculated according to eq. 1 for testpieces where the slot was introduced perpendicularly to the weld line. It is observed that there is a "negative" peak value at approximately 14mm from the edge of the testpiece and K_{rx} remains negative up to the weld centre line. In fact, a "negative" K_r does not exist for a closed crack, but it means that when an external load is applied, the thermal residual stress profile shields the crack, i.e. effectively reduces the local K. The negative values of K_{rx} are likely to produce strong fatigue crack growth deceleration if a crack approaches perpendicularly to the weld line, however after crossing the weld region, K_{rx} are positive and the crack may accelerate, when compared to parent material behavior. It is important to emphasize that such analysis does not take into account the differences in plastic properties of the different regions of the weld which may cause crack retardation or acceleration depending if the crack grows into a soft-hard or hard-soft transition, respectively (Milan and Bowen, 2003, Milan and Bowen 2004a and Milan and Bowen, 2004b). Therefore, when cracks grow in welded structures the effective crack tip driving force will be ruled by a synergistic interaction of the material intrinsic behavior, residual stresses and plastic mismatch between weld regions.

Equation 1 is valid if linear elastic conditions are attained. However, in practical situations, local plasticity ahead of the cut tip and the finite width of the cut may produce non-linear effects. In other words, the strain measured during cutting could be not only the response to the released stresses on the slot faces but also caused by localized plastic yielding immediately ahead of the slot tip. Therefore, as proposed by Schindler (2002), a correction procedure based on the effective crack length (a_{eff}) was applied to the data presented in Figure 4. Details of such procedure are found in Schindler (2000) and will not be described here, for the sake of simplicity. Results show that the difference between corrected and as-calculated K_r values was found to be insignificant and the correction procedure will not be adopted in this paper.

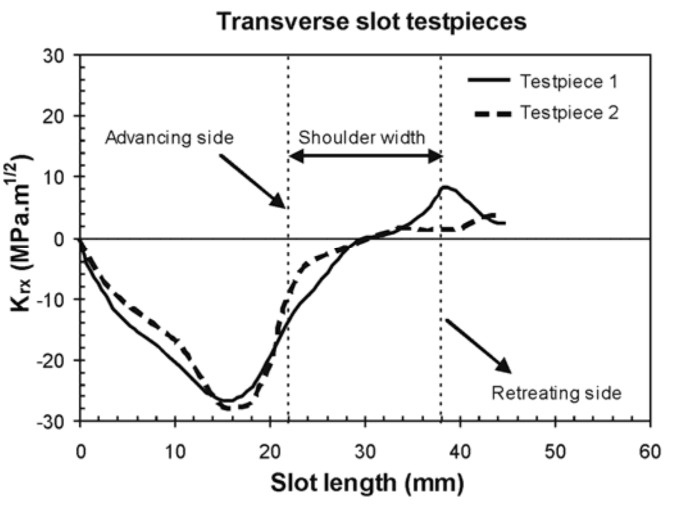

Figure 4. Residual stress intensity factor profiles for transverse slot testpieces.

Using the inverse weight function method, as given by Eq. (6), it was possible to obtain the initial residual stress profile that was present in the material before the slot was introduced, as depicted in Fig. 5. Although, the trends between the results presented in this work and the literature (Peel et al, 2003, Donne et al, 2001 and Staron et, 2004) are the same, a direct comparison seems to be inadequate because the residual stress profile is particularly dependent on testpiece geometry and welding parameters, such as tool geometry and traveling and rotational speeds. Far from the welded region, near the edges of the testpiece, residual stresses are compressive (~ -100MPa). In the welded region there is a peak of tensile residual stress, ranging from 180MPa to 220MPa (50%-60% of parent material yield strength). The peak is localized in the region corresponding to the transition between thermomechanically and heat affected zones on the advancing side of the weld, at approximately 8mm from the weld centre line. Although the residual stresses remain tensile on the retreating side of the weld, at an equivalent distance from the weld centre line (8mm), measured values are significantly lower, ranging from 30MPa to 100MPa (10%-30% of parent material yield strength). Peel et al (2003) and Donne et al (2001) have also shown that the tensile residual stresses on the advancing side of the weld are invariably higher than on the retreating side, however the authors did not offer any explanation for such phenomenon. Donne et al (2001) have shown that, for the same traveling speed, higher rotational speeds produce higher tensile residual stress peaks regions due to the increased frictional heat generation. In this sense, it is possible that the difference in tensile residual stress values in both sides of the weld is the result of different local heat input rates, depending on the relative motion between the material and the tool. On the advancing side of the weld, as a result of a combination of the rotational and traveling movements, the localized frictional heat generation is likely to be larger because the relative speed of the tool in contact with the material is higher. On the other hand, on the retreating side of the weld, the relative speed of the tool surface is given by the difference in the tangential and traveling speed values, resulting in a lower localized heat generation. However, further work is necessary to confirm the assumptions stated above, including a thermal analysis to determine temperature distribution across the weld region during the welding procedure.

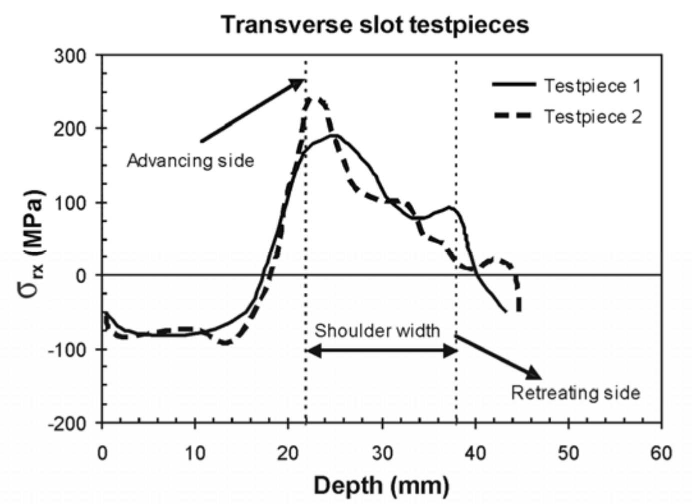

Figure 5. Residual stress profiles for transverse slot testpieces.

Figure 6 depicts several redistributing residual stress profiles for testpiece 1, simulating the growth of a crack into the residual stress field. As the slot gets longer, the residual stress profile is rearranged in order to maintain equilibrium conditions. Additionally, it is possible to observe that the residual stress value in the vicinity of the slot tip remains negative up to approximately the centre of the nugget, although, in the intact testpiece, a positive tensile residual stress field existed in this region. Considering the same distance from the slot tip, it was found that the maximum compressive residual stress is obtained for a slot length of approximately 15mm, which is in agreement with the "negative" peak K_{rx} value observed at this position. It is important to observe that for slot lengths from 5mm to 20mm, the maximum calculated compressive stress at 0,5mm from the slot front is larger than the compressive yield strength of the material (~350MPa, assuming that the yield strength in compression is equal to the value obtained in tension). These singularities are a direct consequence of the inverse weight function analysis which assumes a linear elastic perfect material. In principle, the true stress profile in the vicinity of the slot shall be bounded by the compressive yield strength of the material (excluding any hardening effect), establishing a "cut-off" stress. Therefore, the true stress profiles will be slightly different from those presented in Figure 5, because the area excluded below the "cut-off" stress has to be redistributed within the rest of the curve. However, since this area is normally very narrow, the differences are likely to be insignificant and the redistributed profiles presented in Figure 6 are expected to be a very good approximation of the true stress profile.

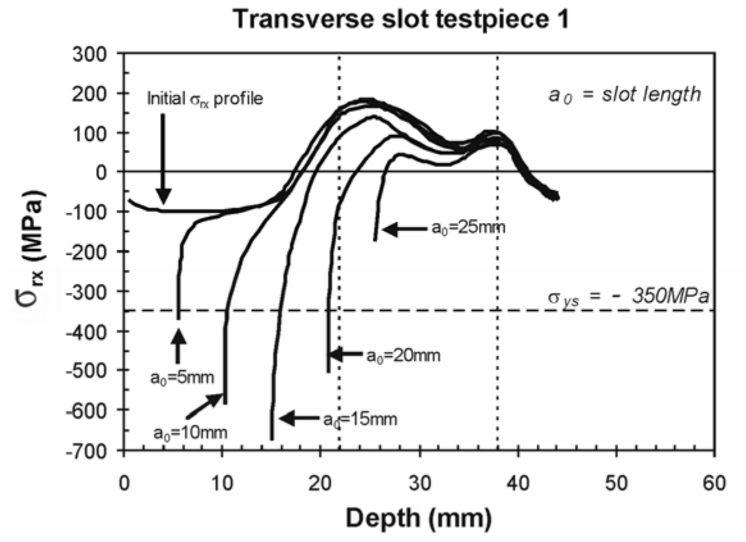

Figure 6. Residual stress redistribution ahead of the slot tip for transverse slot testpiece 1. Vertical dashed lines represent the shoulder width and the horizontal dashed line indicates the "cut-off" stress given by the compressive yield strength of the material.

4.2 Longitudinal slot testpieces

Figure 7 presents transverse residual stress intensity factors, K_{ry}, obtained for longitudinal slot testpieces. In both cases, i.e. for the slot introduced at 0mm and 5mm from the weld center line, K_{ry} values remain negative in the entire range of acquired data. Additionally, it is possible to observe that K_{ry} profiles varies slightly from one testpiece to another and no systematic trend can be established regarding the slot position in relation to the weld center line. However, for both cases, K_{ry} values are much lower than the values obtained in the longitudinal direction, suggesting that cracks growing in a direction parallel to the weld line are likely to be much less affected by the residual stress field produced by the welding procedure.

The initial residual stress profile was also calculated in this case and the results are depicted in Fig. 8. Near the edge of the testpiece, the compressive residual stress can be as high as 120MPa (~34% of yield strength of parent material). This result indicates that an eventual crack nucleation in this region by fatigue mechanisms may be delayed. Towards the centre of the testpiece, a low magnitude tensile residual stress arises to balance the compressive stresses near the edge. Similar trend was observed by Donne and Raimbeaux (2001) and Staron et al (2004) in friction stir welded aluminum alloys. For testpiece 1, as predicted by the K_{ry} profile, the redistributed residual stress profiles presented in Fig. 9 indicate that a compressive residual stress remains present immediately ahead of the slot tip, reaching a maximum value when the slot is approximately 5mm long.

These results demonstrate that a damage tolerant approach must take into consideration the redistribution of stresses ahead of a crack tip if an accurate estimate of the stress field is required. In this sense, the inverse weight function method proved to be an extremely valuable tool to understand the stress field behavior in cracked components.

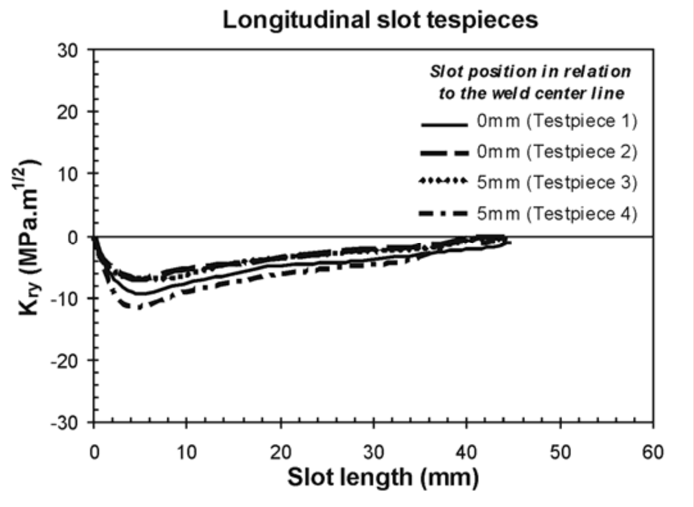

Figure 7. Residual stress intensity factor profiles for longitudinal slot testpieces.

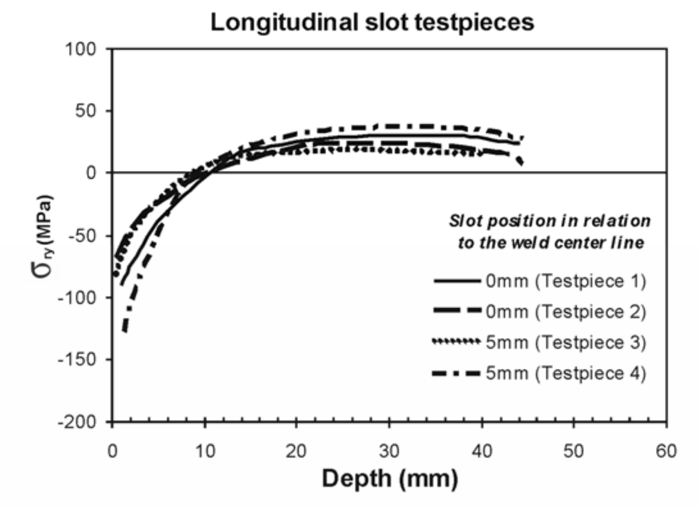

Figure 8. Residual stress profiles for longitudinal slot testpieces.

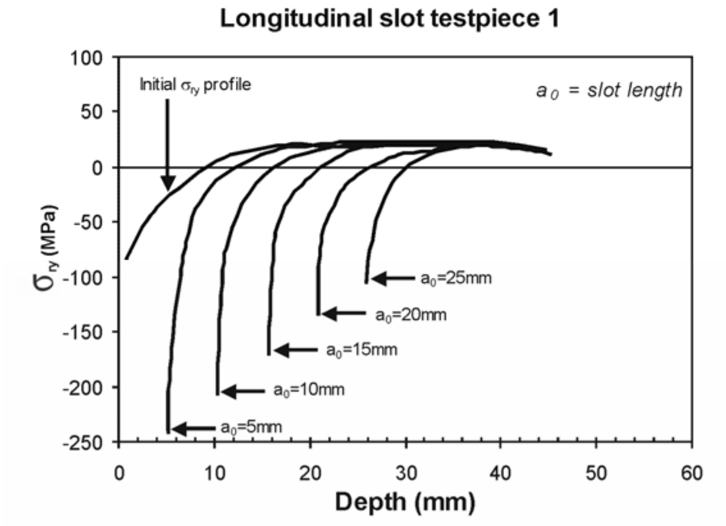

Figure 9. Residual stress redistribution ahead of the slot tip for longitudinal slot testpiece 1.

5. Conclusions

1. Longitudinal residual stresses in AA2024-T3 friction stir welded plates, 3.2mm thick, present a peak tensile residual stresses located in the thermomecanically/heat affected zones, on the advancing side of the weld, ranging from 50% to 60% of the yield strength of the parent material. Tensile residual stresses are higher on the advancing side of the weld, probably because of the larger heat input, resulting from the higher relative speed between the tool and the material.

2. Transverse residual stresses have a bow-like shape, presenting large compressive residual stresses (~ -100MPa) near the edges of the rectangular testpiece and low magnitude tensile residual stresses in the centre of the plate.

3. The inverse weight function method proved to be an effective tool to understand the trends of residual stress redistribution in cracked components and valuable information can be obtained to be employed in damage tolerant designs.

6. Acknowledgments

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