# AN INDIRECT METHOD FOR CALCULATE WELD RESIDUAL STRESSES VIA FATIGUE CRACK GROWTH TEST DATA

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***Abstract.*** *Friction stir welding (FSW) is a solid-state process of welding technique with considerable capability to join aluminum alloys with high mechanical properties such as Al 2024-T3 which has wide use in construction of aircraft structures. Damage tolerant structures are mandatory for civil aircraft, and it is based on fatigue crack propagation analysis. Since residual stress arising from the weld process may affect fatigue crack propagation, it is important to determine the residual stress distribution. Therefore, this paper presents a method for evaluating weld residual stresses via fatigue crack growth test data. The material data and variables considered at this method are: stress intensity factor K that is a measure of the severity of a crack situation, da/dn x DeltaK curve that is the relationship between cyclic crack growth rate da/dn and stress intensity factor range that describe the crack growth behavior, and R that is the ratio between minimum K value and the maximum K value. Thus, a investigation, that consider the change of R due to residual stress, is done based on the Walker equation and the residual stress distribution is determined as well as it is evaluated the effect of R in residual stress distribution for ductile structure metal as Al 2024-T3.*

***Keywords****: residual stress; friction stir welding; fatigue crack growth.*

## 1. INTRODUCTION

Since the early 1970, there have been significant developments in the state-of-the-art and industry-practice in the area of structural-fatigue strength evaluation for transport category airplanes. One of the most important concepts is the damage tolerant structure.

The damage tolerant conception seek to evaluate a structural design that under typical loading and environment condition must show that catastrophic failure due to fatigue loads, accidental damage or corrosion will be avoided throughout the operational life of aircraft.

Fatigue damages are represented for small cracks which growing during the life of a structural component leads to fatigue failure. These cracks can be pre-existed at the time of manufacturing or be created by in-service load conditions (Noroozi A.H., Glinka G. and Lambert S., 2007). Therefore, the crack growth should be predictable to provide guidelines for inspection programs, which ensure that cracks will be found before they reach the critical size that threatens the structural integrity.

In the last decade, research in manufacture of aircraft structure is seeking to create integral structures via processes such as friction stir welding (FSW) rather than the traditional riveting, that represent crack initiation sources due to stress concentration (Servetti G. and Zhang X., 2009). Integral structure aims manufacture cost saving, structural weight reduction, as well significant decrease or complete removal of numerous fasteners in joint areas of the airframe resulting in much improved fatigue endurance and inspection simplifications.

However, an inherent inconvenience is the residual stresses present in welded structures after fabrication. These residual stresses can affect mechanical and corrosion properties of the materials, influencing the in-service performance of structural components related to material strength and fatigue crack propagation (Milan M. T., Tarpani J. R. and Bose Filho, 2005).

The fatigue crack propagation is affected by tensile residual stresses that increase the crack growth rate by an increase in the effective stress ratio and/or stress intensity factor, and the opposite effect is related to compressive residual stresses. These changes in effective stress ratio and/or stress intensity factor due to residual stress will modify the crack propagation curves of material that will ultimately modify the maintenance plan of aircraft that use FSW in construction of structural components.

The aim of this paper is to determine the residual stresses in AA2024-T3 friction stir welded joints perpendicularly to the welding line, using the concepts defined by Paris equation, Walker equation and the Principle of Superposition.

## 2. FSW RESIDUAL STRESS ANALYSIS

In early 1960s, Paul Paris defined that, for a given material, the crack growth behavior through the relationship between cyclic crack growth rate da/dN and stress intensity factor range ΔK is as follow (Dowling N. E.,1999):

$$\frac{da}{dN} = C(\Delta K)^m \tag{1}$$

At the intermediate values of ΔK, there is often a straight line on the log-log plot, where C is a constant and m is the slope on log-log plot (Dowling N. E.,1999).

The mean stress level is characterized by the stress ratio, R, which is defined as:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} = \frac{K_{\min}}{K_{\max}} \tag{2}$$

The coefficient C and exponent m of the Paris equation are dependent of materials properties and the R-ratio is related to the applied cyclic loading (Huang X and Moan T, 2007). Under different R-ratios, the crack growth rates expressed as a function of ΔK are shown schematically in Fig. 1. It can be concluded that R-ratio has a significant effect on the crack growth rate and only the stress intensity factor range ΔK is unable to explain the crack growth rate under different R ratios (Huang X and Moan T, 2007).

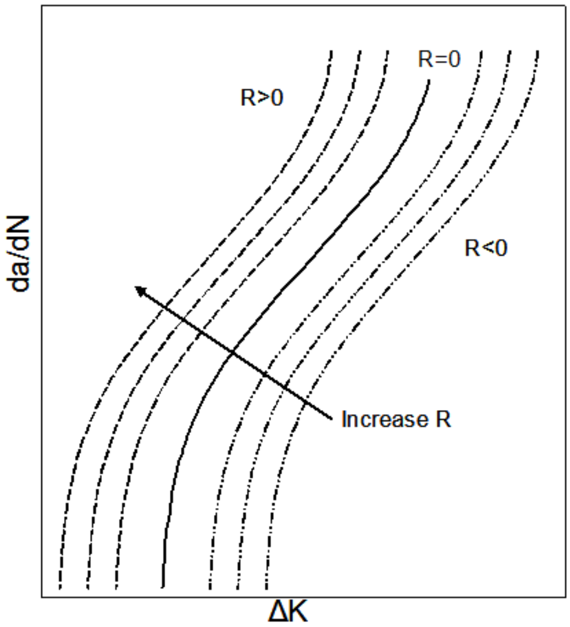

Figure 1. Cyclic crack growth rate da/dN x ΔK under different R

Several researchers have tried to establish the relationship considering the effect of the stress ratio through mean stress equations, among which, it can be mentioned Elber and Walker.

Elber was the first who studied crack closure to be the main reason for the crack propagation rate to vary with R. He observed that, at low loads, the compliance of test specimens was close to that of an uncracked specimen. He introduced the concepts of crack closure and the effective stress intensity factor range ΔKeff as the preponderant driving force for fatigue crack growth. Crack closure may be caused by compressive loads, mismatch of surface roughness, plastic deformations behind the crack tip or the buildup of a surface layer (Mann T., 2007). Thus, the crack growth rate can be expressed as:

$$\frac{da}{dN} = C(\Delta K_{eff})^m \tag{3}$$

$$\Delta K_{eff} = K_{\max} - K_{op} \tag{4}$$

Where, $K_{max}$ is the maximum stress intensity factor calculated for the maximum load $P_{max}$, and $K_{op}$ is the stress intensity factor value for the crack opening load $P_{op}$.

According to (Dowling N. E., 1999), another approach to describe the mean stress dependence was suggested by Walker. The Walker equation is an empirical model based on test data and curve fitting analysis. It is expressed as values onto a single curve or narrow band that predicts the fatigue crack growth rate data at various R values (Zheng J. and Powell B.E., 1999) as follow:

$$\overline{\Delta K} = K_{\max}(1-R)^{\gamma} \tag{5}$$

Where, $\gamma$ is material constant and $\overline{\Delta K}$ is equivalent zero-to-tensile stress intensity that causes the same crack growth rate as the actual $K_{max}$ . Eq. (5) is equivalent to:

$$\overline{\Delta K} = \frac{\Delta K}{(1-R)^{1-\gamma}} \tag{6}$$

Let the material constants C and m in Eq. (1) be denoted $C_1$ and $m_1$ for the special case of R = 0. Since $\overline{\Delta K} = \Delta K$ for R = 0, it is possible to substitute $\overline{\Delta K}$ for $\Delta K$ in the special case, giving:

$$\frac{da}{dN} = C_1\left[\frac{\Delta K}{(1-R)^{1-\gamma}}\right]^{m_1} \tag{7}$$

Eq. (7) represents a family of da/dN versus ΔK curves, which on a log-log plot are all straight lines of slope $m_1$ as shown schematically in Fig. 2 and, after some manipulations, results in:

$$\frac{da}{dN} = \frac{C_1}{(1-R)^{m_1(1-\gamma)}}(\Delta K)^{m_1} \tag{8}$$

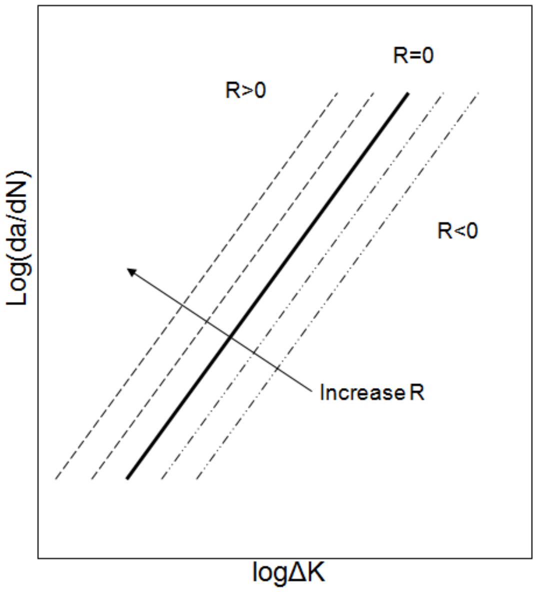

Figure 2. Family of da/dN versus ΔK curves with slope $m_1$

Thus, constants C and m for Eq. (1) are:

$$C = \frac{C_1}{(1-R)^{m_1(1-\gamma)}} \qquad m = m_1 \tag{9}$$

The intercept constant C is predict to be a function of R, but the slope m is unaffected by R, and an interpretation arising from Eq. (7) is that $\overline{\Delta K}$ , the equivalent zero-to-tensile (R = 0), can be plotted versus da/dN resulting in a single straight line (Dowling N. E., 1999).

However, it is necessary to assume that the compressive portion of the cycle, R < 0 has no effect, which is accomplished by using $\gamma = 0$, so $\Delta K = K_{max}$.

The material constant γ can be determined from data at various R values by a trial and error procedure, where the γ value found is that one that best consolidates the data along a single straight line or other curve on a plot of da/dN x $\overline{\Delta K}$ .

Another useful concept is the Superposition Principle. This principle states that for linear elastic material, individual components of stress, strain, and displacement are additive. For example, two normal stresses in the x direction imposed by different external forces can be added to obtain total normal stress, but a normal stress cannot be summed with shear stress.

One more general concept, namely stress acting on the boundary or tractions, can be replaced with tractions that act on the crack face, such that two loading configurations result in the same stress intensity factor as illustrated in Fig. 3, (Anderson T. L., 1995).

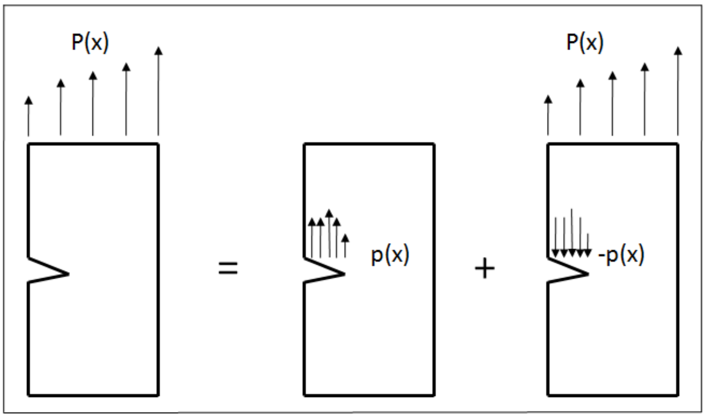

Figure 3. Stress acting on the boundary or tractions

## 3. PROPOSED METHOD

Based on the fracture mechanics concepts presented above, the proposed method for evaluating weld residual stresses considering fatigue crack growth test data is shown as follow.

Considering the results of fatigue crack growth test da/dN and ΔK, the material constant C is calculated for each crack size according to Eq. (1). Since $C_1$ and γ values are known, and taking the logarithm for both side of Eq. (8), it is possible to determine R value as follow:

$$R = 1 - 10^{\frac{\log \frac{C_1}{C}}{m(1-\gamma)}} \tag{10}$$

If it is taken into account the residual stress $\sigma_{res}$ at Eq. (2) as follow and solving for $\sigma_{res}$:

$$R = \frac{\sigma_{\min} + \sigma_{res}}{\sigma_{\max} + \sigma_{res}} \tag{11}$$

$$\sigma_{res} = \frac{R\sigma_{\max} - \sigma_{\min}}{(1 - R)} \tag{12}$$

According to Eq. (12) by considering the concept of stress acting on the boundary or tractions, it is possible to calculate transverse residual stress $\sigma_{res}$ for each crack size from test data. Transverse residual stress means the stress acting perpendicularly to the welding line.

## 4. RESULTS

Firstly, plates of AA2024-T3, 1.6 mm thick, were friction stir welded along the rolling direction. Then, 150x284 $mm^2$ rectangular test samples were machined according to middle-crack tensile, M(T), as represented in Fig. 4. The next step was to perform fatigue crack growth test.

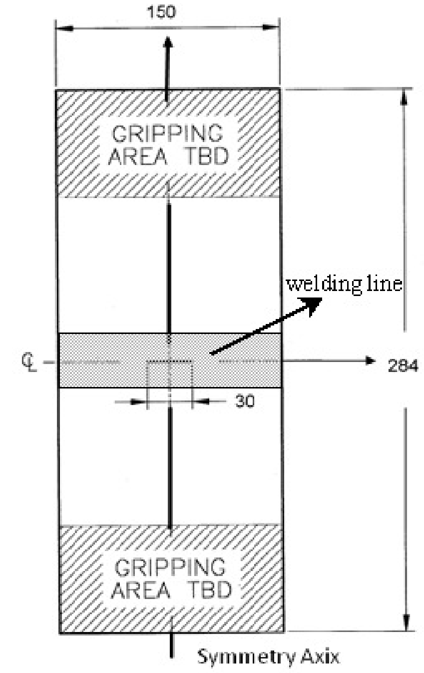

Figure 4. Test samples middle-crack tensile M(T)

Three samples were tested: test sample (a) and (b) with initial crack of 30 mm, and test sample (c) with initial crack of 15 mm. The results presented consider vertical symmetry as shown in reference axis of Fig. 4.

Figures 5 to 7 present the R values calculated for test samples (a), (b) and (c) respectively. It is observed that sample (a) shows that most of data points of stress ratio R remains into a band between 0.5 and 0.6. It is observed that sample (b) shows that most of data points of stress ratio R remains into a band between 0.4 and 0.6, and sample (c) shows that the most of data points of stress ratio R remains into a band between 0.6 and 0.7. Test sample (a) shows more homogeneous results without discrepant values comparing with sample (b) and (c). These discrepancies can be explained by eventual problems related with data acquisition of a x N during fatigue crack growth test, and it will be evidenced in residual stress results for test sample (b) and (c).

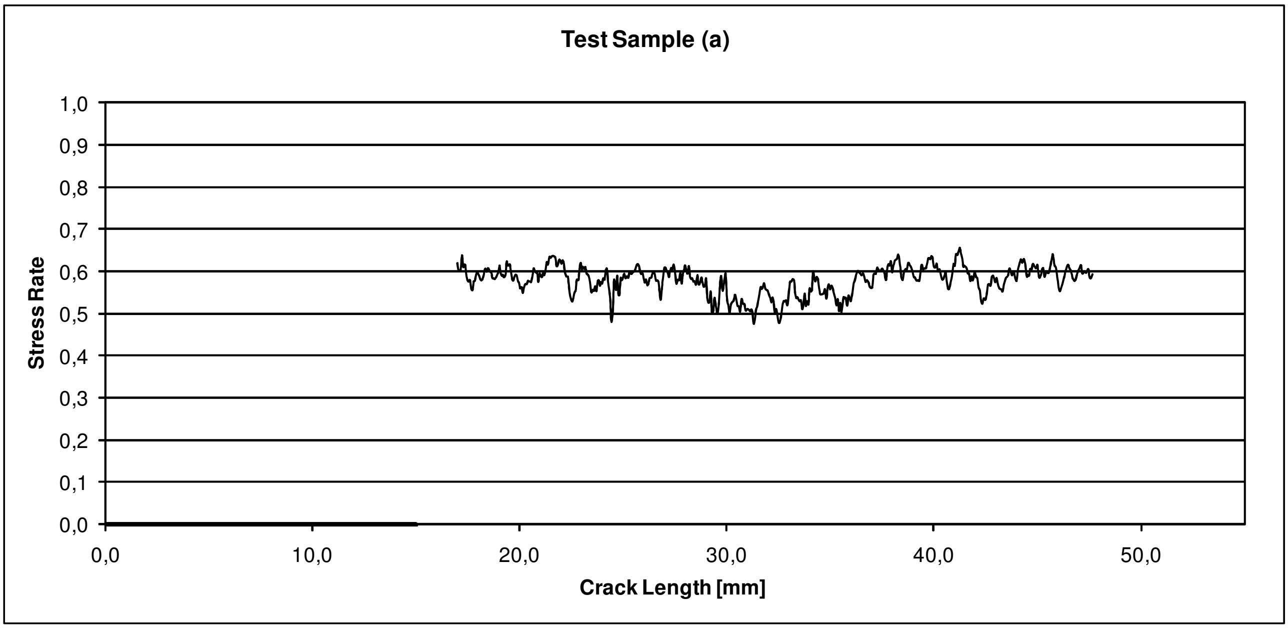

Figure 5. R value for test sample (a)

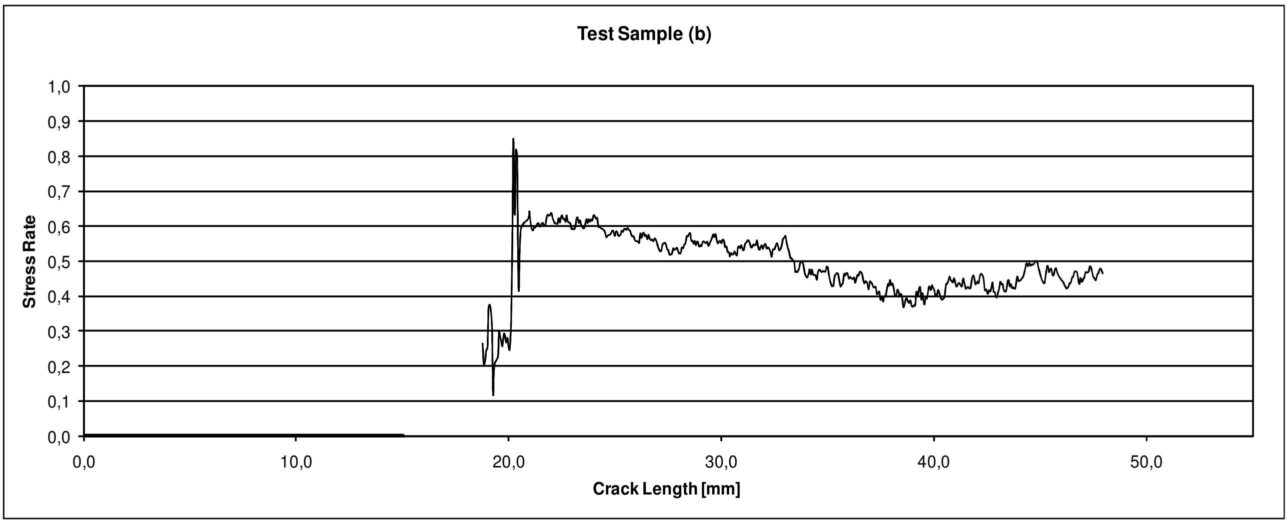

Figure 6. R value for test sample (b)

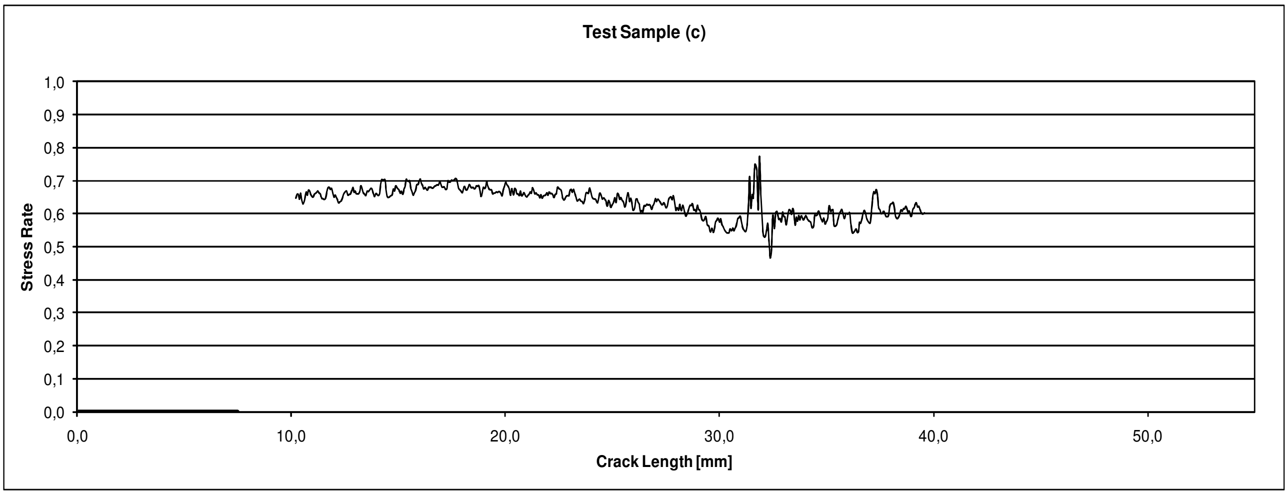

Figure 7. R value for test sample (c)

Figures 8 to 10 present the residual stress calculated for test samples (a), (b) and (c) respectively. The residual stress plot scales were truncated at 80 MPa to make the results comparison clearer. It is observed that sample (a) shows that most of data points of residual stress remains into a band between 20 MPa and 40 MPa. Sample (b) shows that the most of data points of residual stress remains into a band between 10 MPa and 40 MPa, and sample (c) shows that the most of data points of residual stress remains into a band between 25 MPa and 50 MPa. Considering the minimum and maximum limits presented above, it can be observed that residual stress calculated varies between 2.8 % and 14 % of yield strength of parent material.

It is important to comment that residual stress calculated by the proposed method can be an equivalent residual stress, because besides the own residual stress, other factors could influence crack propagation behavior in the weld region as: exfoliation corrosion, oxide particles, joint microstructures or dissolution of larger precipitates and reprecipitation in the weld center. However, the residual stress obtained can be useful for practical application in fatigue and damage tolerance analysis.

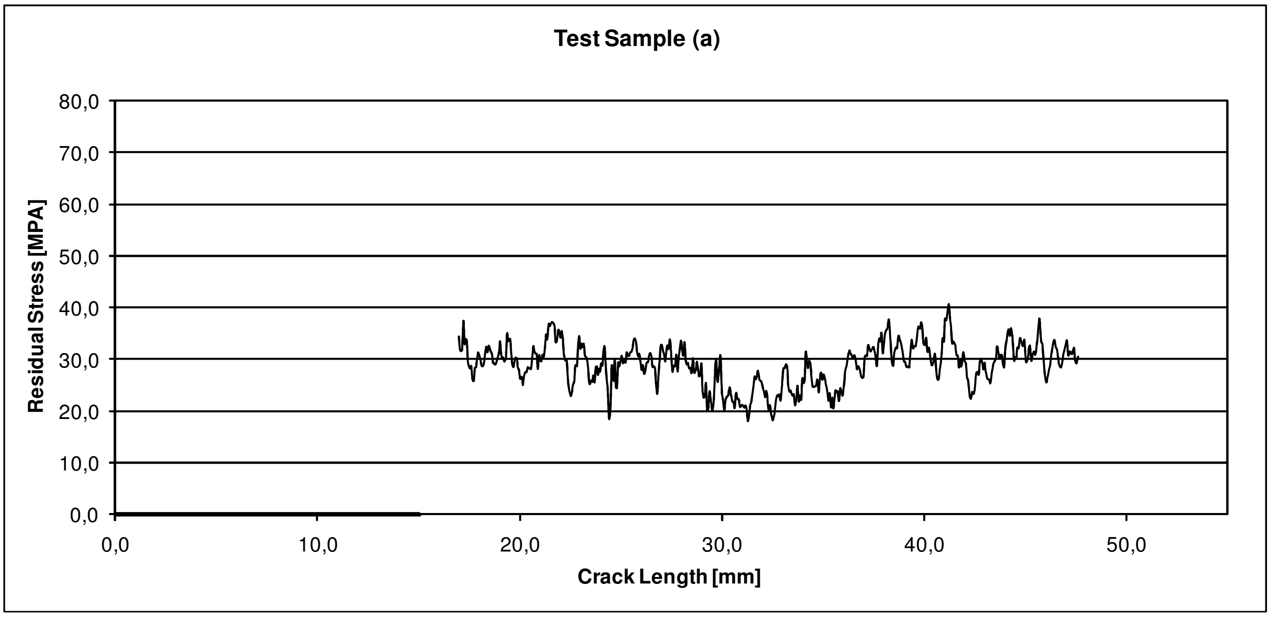

Figure 8. Residual stress for test sample (a)

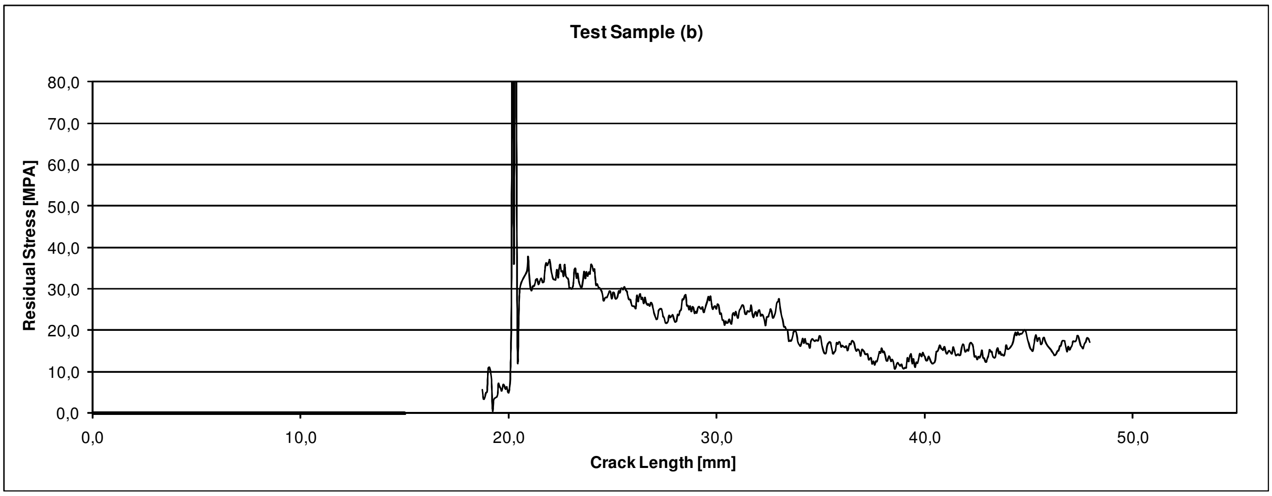

Figure 9. Residual stress for test sample (b)

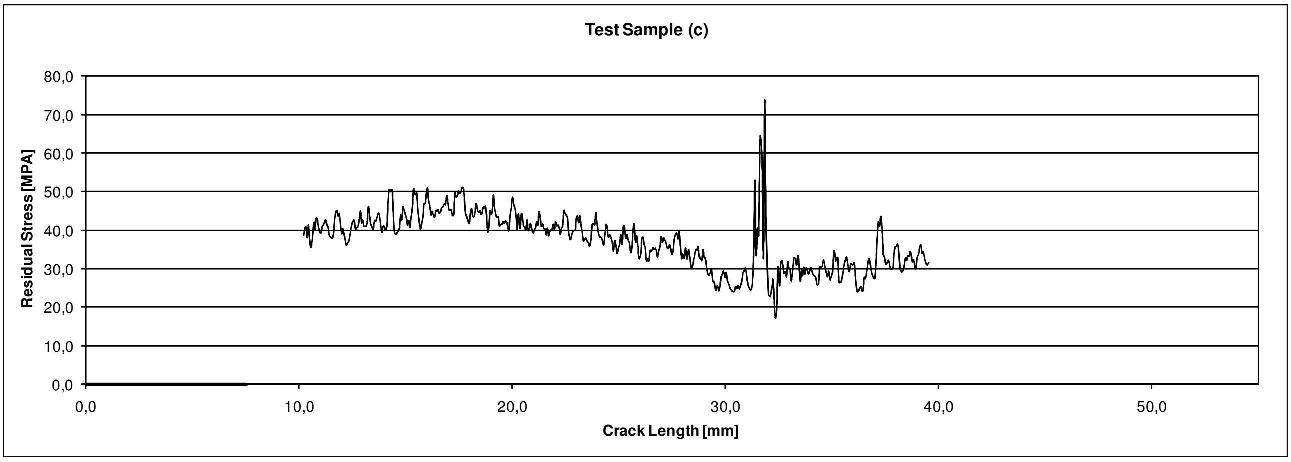

Figure 10. Residual stress for test sample (c)

(Milan M. T., Tarpani J. R. and Bose Filho, 2005) presents a measure of transverse residual stresses in 3.2 mm thick AA2024-T3 friction stir welded joints using the crack compliance method together with the inverse weight function method. The residual stress value published for a wide compact tensile specimen C(T) is between 20MPa and 40MPa.

(Fratini L. Macaluso G. and Pasta S., 2009) calculates by finite element analysis the actual thermal flow occurring during a FSW process. Such thermal histories is passed to a further elasto-plastic finite element model, then, the numerical residual stresses is determined for AA2024-T4 aluminum alloy 3mm thick. The published transverse residual stress is around 45MPa.

In the first part of (Donne, C. D., Lima E. and Buslaps T., 2001), cut compliance data of the a wide compact tensile specimens C(T) in 4 mm thick aluminum alloy sheets 2024-T3 is shortly reviewed, and the residual stress distribution is calculated using the inverse weight function method. The published peak transverse residual stress is 35MPa.

It is observed that the results calculated by the proposed method are very similar in absolute values with the results published by (Milan M. T., Tarpani J. R. and Bose Filho, 2005), (Fratini L. Macaluso G. and Pasta S., 2009) and (Donne, C. D., Lima E. and Buslaps T., 2001), although the FSW process parameters and thickness of aluminum alloy sheets are different.

The distribution of stress calculated by the proposed method is not similar to the results find in (Milan M. T., Tarpani J. R. and Bose Filho, 2005) and (Donne, C. D., Lima E. and Buslaps T., 2001), where, the highest values of tensiles are in the center of the samples with high compressive stress in regions near the sides of the samples. However, according to (Donne, C. D., Biallas G., Ghidini T. and Raimbeaux G, 2000), this difference occurs due to the influence of test specimen geometry on da/dN x ΔK curves. After machining the specimens, compressive residual stresses arise at the crack tip of a C(T) specimen, while tensile stresses are observed at the crack tip of M(T) specimen , as shown in Fig. 11.

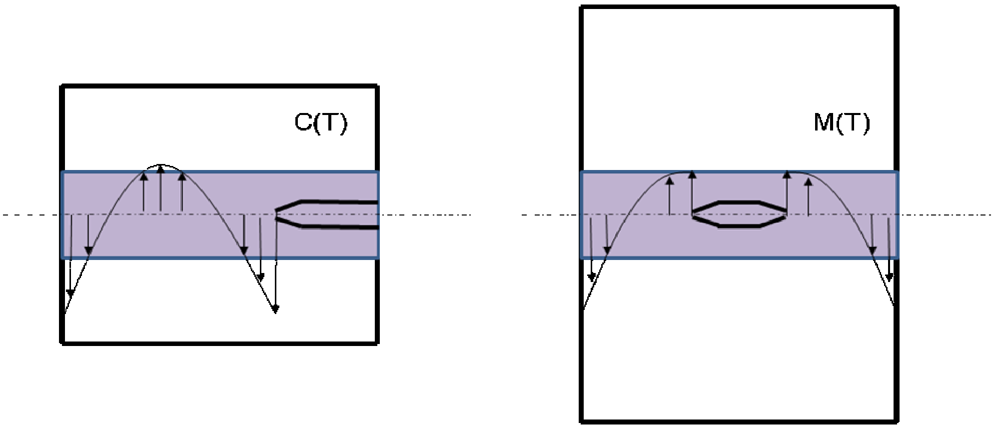

Figure 11. The influence of test specimen geometry on residual stress distribution

## 5. CONCLUSIONS

Residual stress analysis on friction stir welds was carried out by the proposed method that considers da/dN x ΔK curves from fatigue crack growth test. The quality and accuracy of the test data are very important to the results calculated by the proposed method. The results calculated are in good agreement with the results found by others researchers considering the same material.

The transverse residual stress found in this paper reached values of up to 50 MPa, which may represent a great influence on the fatigue and damage tolerance analysis for the structural components of aircraft.

The proposed method has demonstrated to be a practical and economical tool for the calculation of transverse residual stresses, since it is possible to obtain the residual stresses in welds of type FSW with sufficient data in terms of number of cycles and crack size from a typical fatigue crack growth test.

Future investigation about the proposed method must be performed, but this method can substitute other methods to obtain residual stress in welded structures as: sectioning method, Hole drilling method or X-ray diffraction method.

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