EVALUATION OF RESIDUAL STRESSES DURING FATIGUE TEST IN A FSW JOINT

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ABSTRACT

This paper shows an application of the adjusted compliance ratio method, ACR, and the on-line crack-compliance technique for determination of the effects of the residual stress during a fatigue test. The fatigue crack growth tests were carried out on a friction stir welded joint in Ti-6Al-4V titanium alloy. The on-line crack-compliance enables the determination of the residual stress intensity factor in real-time from a fatigue test. The ACR methodology was used to separate the closure and residual stress effects from the crack growth rate data. Finally, the residual stress distribution of the FSW joint was found from the knowledge of the residual stress intensity factor through an integral solution. It would have to be noted that both methods are based on ratios of displacements; therefore, the practical application does not require the use of the influence functions needed for the cut compliance method. Moreover, a specific test, which determines the residual stresses, can be avoided because the effect of the same residual stresses on the crack growth is evaluated during the fatigue test.

Nomenclature

- \( a_n \): crack length at \( n \) step
- \( a_{n+1} \): crack length at \( n+1 \) step
- ACR: adjusted compliance ratio
- \( C_i \): compliance of notch before crack initiation
- \( C_{op} \): compliance above opening load
- \( C_s \): secant compliance
- \( \Delta \delta_{\text{max}} \): change in displacement at maximum load due to change in crack length
- \( \Delta \delta_{\text{res}} \): change in displacement due to residual stress and change in crack length
- \( K_{\text{app}} \): stress intensity factor due to applied load
- \( K_{\text{eff}} \): effective stress intensity factor
- \( K_{\text{max}} \): stress intensity factor due to maximum load
- \( K_{\text{min}} \): stress intensity factor due to minimum load
- \( K_{\text{op}} \): stress intensity factor above opening load
- \( K_{\text{res}} \): stress intensity factor due to residual stress
- \( P_0 \): zero load
- \( P_{op} \): opening load
- \( P_{\text{max}} \): maximum load
- \( P_{\text{min}} \): minimum load
- \( \Delta \delta_{\text{app}} \): closure free displacement range
- \( \Delta \delta_{\text{eff}} \): actual measured displacement range
- \( \Delta \delta_i \): measured displacement range before crack initiation
- \( \Delta K_{\text{app}} \): applied stress intensity factor range
- \( \Delta K_{\text{eff}} \): effective stress intensity factor range
- \( R \): stress ratio
- \( W \): compact tension width
Introduction

Many authors [1-4] have shown with experimental tests and numerical simulations that the damage tolerance of FSW joint is significantly influenced by the residual stress and that the microstructure and hardness changes have a minor effect. Therefore, a technique to estimate with accuracy the influence of the residual stress and a method to separate the closure effect would have to be used in order to evaluate the crack growth behavior in a FSW joint. Moreover, when using the effective stress intensity factor, $\Delta K_{\text{eff}}$, to estimate the crack growth rate, the most important and difficult part is to measure precisely the closure effect and determine consistently the crack opening load, $K_{op}$ [5]. In this way, the on-line crack-compliance and ACR methodologies [6-8] can be utilized with success to determine the fatigue life of FSW joint.

Generally, several experimental techniques permit to evaluate the residual stress field developing in FS welded joint. Diffraction methods (e.g. x-ray and neutron diffraction techniques) can provide information on the longitudinal and transverse residual stress fields; however, these methods require expensive equipment and may at times be confounded by issues such as crystallite size and crystallographic texture. The destructive cut compliance method described by Prime [9] is widely used to provide the through-thickness residual stress intensity factor of a supposed crack front. Subsequently, the residual stress profile is analytically calculated from the residual stress intensity factor, $K_{res}$. Similarly, the hole drilling method [10] provides the residual stress distribution by means of incremental hole-drilling steps and numerical routines. Nevertheless, these destructive techniques require the knowledge of the influence functions which depend on the cut depth, the strain gage location and the geometry of the investigated specimen. Also, it has been recently illustrated that the innovative techniques of the contour method described by Prime et al. [11, 12] can also adopted to measure the residual stress in FSW joints: this technique can provide detailed information but also requires relatively elaborate experimental setup and numerical analysis.

In a different way, the on-line crack-compliance and ACR methods evaluate the influence of residual stress on the crack growth during fatigue test. A ratio of displacement is used to compute the $K_{res}$: therefore, a clip gage is needed to provide the measurement of the compliance during the fatigue crack growth test. Critical to accurate application of these methodologies are sufficient signal stability and signal linearity measured at the specimen load line to determine the $K_{res}$. However, by comparison to most other techniques, both methods are simple and convenient to use.

In this paper, fatigue crack growth tests were carried out and the on-line crack compliance and ACR methods were used to assess the effect of the residual stresses on the crack growth behavior of a FSW joint. The software and the data acquisition system, which are provided by the Fracture Technology Associates, FTA, was used to carry out the fatigue test in K-control and to obtain the $K_{res}$ profile. Specimen compliance was measured continuously to calculate the crack length and to provide feedback to the software. The fatigue tests were carried out on FSW butt joints in Ti-6Al-4V titanium alloy. The experimental work has provided the $K_{res}$ profile (as a function of position relative to the FSW) and the residual stress field has been correlated to the crack growth rate. The residual stress intensity factor profile obtained by the ACR method is compared to the values obtained from the cut compliance method.

Methodology

The on-line crack compliance method

The real-time evaluation of $K_{res}$ during fatigue crack growth testing can be obtained from the on on-line crack compliance method. The fatigue tests were carried out in K-control mode and the compliance method of monitoring the crack length has to be used in order to adjust the stress state at crack tip during the fatigue test. The on-line crack compliance method is similar to the cut compliance technique described by Prime [9]; however, he specifies the use of the influence functions depending from the cut depth, the strain gage location and the geometry of the investigated specimen. The $K_{res}$ profile can be extrapolated from the slope of the load–displacement curve, Figure 1 [6], down to a displacement corresponding to zero load, $P_0$. When the crack advances, a decrease in displacement of clip gage at zero load implies a negative $K_{res}$, i.e. compressive $K_{res}$. In a different way, an increase in displacement means positive $K_{res}$, i.e. tensile $K_{res}$. Tensile residual stress evaluation is simply provided from the tendency of crack opening to minimize the crack closure effect, Figure 1 (A). Compressive residual stress is measured from slope of the load-displacement curve above the closure level, Figure 1 (B). $K_{res}$ is provided by measuring the changes of displacement at maximum load, $P_{\text{max}}$, for a given increment of crack length and comparing this value to the corresponding change of displacement at zero load over the same increment of crack length. The ratio of the displacement change at zero load, $d\delta_{\text{res}}$, to the displacement change at maximum load, $d\delta_{\text{max}}$, is proportional to $K_{res}$:

$$K_{res} = K_{\text{max}} \frac{d\delta_{\text{res}}}{d\delta_{\text{max}}}$$

The on-line crack-compliance is easy to use; however, it necessitates a sufficient signal stability and linearity of the measurement at load-line of testing specimen.
The adjusted compliance ratio, ACR, method

The ACR methodology permits to separate from fatigue crack growth data the closure effects caused by residual stress and other mechanisms. Therefore, the effective stress intensity factor range, $\Delta K_{eff}$, can be obtained from the ACR method. As specified for the opening load method [13], the load-displacement curve is used; however, the ACR method also considers the crack tip activity below the opening load, $P_{op}$. In fact, the interactions of the mating broken faces along the crack wake are taken into account by the strain fields below the stress intensity factor opening the crack mouth, $K_{op}$. Below $K_{op}$, the stress intensity factor caused by closure effects is added to the stress intensity factor due to minimum load, $K_{min}$. Above $K_{op}$, only the applied stress intensity factor, $K_{app}$, contributes to the crack growth.

The ACR technique, Figure 2, uses remote compliance measurements and is determined by subtracting the compliance prior to the initiation of a crack, $C_i$, from both the secant compliance, $C_s$, and the compliance above the opening load, $C_{op}$:

$$ACR = \frac{C_s - C_i}{C_{op} - C_i}$$

Where:
- $C_s = \frac{\Delta \delta_{eff}}{\Delta P}$ is the inverse slope of secant drawn between minimum load-displacement and maximum load-displacement;
- $C_{op} = \frac{\Delta \delta_{app}}{\Delta P}$ is the inverse slope of load-displacement above opening load;
- $C_i = \frac{\Delta \delta}{\Delta P}$ is the inverse slope of load-displacement prior to initiation of a crack (notch).

By computation of the ACR, the $\Delta K_{eff}$ can be calculated:

$$\Delta K_{eff} = \frac{C_s - C_i}{C_{op} - C_i} \cdot \Delta K_{app}$$
Titanium alloys Ti-6Al-4V titanium sheet, 2 mm thick, was used for all experiments. The parent material plates (width=300 mm, length=510 mm) were friction stir welded along their long edge and parallel to the rolling direction. The welds were carried out under z-axis load control at 150 rpm rotation speed and at 100 mm/min welding speed. The welding tool was fabricated out of a W-25% Re alloy.

Fatigue crack propagation tests were conducted with compact tension (CT) specimens in accordance with the ASTM E 647-91 (1991) [13]. The CT specimen was 2 mm thick with W=60 mm. The welding line was placed perpendicular to the notch. The initial notch tip was at a/W=0.2 and the weld centerline was at a/W=0.46. The crack approaches the weld from the advancing side.

A constant $\Delta K$-control test was performed to evaluate the effect of the residual stress on the crack growth behavior of the FSW joint. Based on the fatigue crack growth behavior of the base material, a constant $\Delta K_{app}=30$ MPa m$^{1/2}$ value was chosen. The CT specimens were tested with a MTS servo-hydraulic fatigue machine with a 22 kN load cell and at R=0.1 and 10 Hz. The compliance method was used for monitoring the crack length. Particularly, a clip gage located on the front face of CT specimen provides the compliance measurement. This method has the advantage of high resolution and takes into account the closure effects. Both on-line crack compliance and ACR methods were adopted by using the data acquisition system provided by the Fatigue Technology Associates. The acquisition system comprises a device for digital signal processing interfaced with the MTS fatigue testing machine and a software for the crack growth analysis in $K$-control mode. Load shedding was monitored through the FTA software and the specimen compliance was measured continuously to calculate the crack length and to provide feedback to the fatigue software.

The cut compliance method described by Prime [9] was also used to obtain the residual stress intensity factor profile for a crack growing perpendicular to the weld. The method measures the release of the residual strain caused by a saw cutting progressively introduced along the supposed crack front. Introducing a narrow cut into the closure zone, the residual stress intensity factor is directly provided from the measure of a strain gage on the back-face.

**Results and discussion**

As described in the methodology section, fatigue crack growth under conditions of constant applied $\Delta K_{app}$ has been measured and residual stress intensity factor profiles have been measured via the ACR method and the cut compliance method. Residual stress profiles have been calculated from the residual stress intensity profiles by numerical inversion of the appropriate weight function integral equation.
It has been widely recognized that the crack growth rate depends from the effective stress intensity factor range, $\Delta K_{\text{eff}}$, i.e. the measurement of the closure effects and opening load. Figure 3 shows that the crack growth rate as a function of position relative to the weld centerline. In the absence of residual stress effects, it is expected that the crack growth rate would be constant since the test was conducted under conditions of constant applied $\Delta K$. However, as can be seen in the Figure 3, the actual behavior is not consistent with the constant crack driving force. The $da/dN$ is considerably relative to the baseline behavior as the crack approaches the weld region. As the crack grows into and then through the weld, $da/dN$ increases and then reaches a constant value.

During the fatigue test, the effective stress intensity factor range, $\Delta K_{\text{eff}}$, is the difference between the maximum stress intensity, $K_{\text{max}}$, and the stress intensity at crack opening, $K_{\text{op}}$. The actual stress intensity at the crack tip will be the linear sum of the applied stress intensity factor, due to the externally applied loads, and the residual stress intensity resulting from the residual stress produced by the friction stir welding process. Figure 4 shows the residual stress intensity factor profile obtained using the ACR method during the fatigue crack growth test of the FSW joint. The stress intensity factor profile displays an interesting form for the crack approaching the weld from the advancing side. First, it decreases to a minimum on the advancing side, and then rises to a maximum in the weld zone. Moreover, the negative values of the residual stress intensity factor are well equilibrated by the positive values. The stress intensity values shown in Figure 4 are the values that should be added to the applied stress intensity in order to determine the stress intensity present at the crack tip. As negative stress intensities are not expected to produce damage at the crack tip, the crack growth rate should be reduced relative to the baseline in the region where the weld residual stress causes a negative stress intensity to be added to the applied stress intensity. As can be seen by comparison of Figures 3 and 4, the position of the minimum in the residual stress intensity factor (the greatest negative value) corresponds very closely to the minimum in the observed fatigue crack growth rate.
Outside the weld, the residual stress intensity determined by the ACR methodology correctly estimates the closure effects caused by the residual stress due to the FSW process. Differently, inside the weld, the positive stress intensity factor values suggest tensile residual stresses. The compressive residual stresses outside the weld zone determine high values of the residual stress intensity factor range, $\Delta K_{\text{res}}$, so that the effective stress intensity factor range, $\Delta K_{\text{eff}}$, assumes low values and the crack growth rate is reduced. Then, the residual stress acts in opposite way and the $\Delta K_{\text{eff}}$ increases as the $K_{\text{res}}$ approaches zero and then becomes positive. Finally, the residual stress distribution has been calculated from the ACR derived residual stress intensity profile through a closed inverse integral solution on the base of Schindler’s technique [14]: the calculated residual stress profile is shown in Figure 5.

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**Figure 4** Residual stress intensity factor profile, $K_{\text{res}}$, as a function of the distance from the weld centerline; the evaluation is provided from the on-line crack-compliance and ACR methods.

**Figure 5** Longitudinal residual stress distribution as function of the distance from the weld centerline: the profile is obtained with a closed inverse solution.
In Figure 5 it can be noticed tensile residual stresses inside the weld zone with the external regions subjected to compressive residual stresses. The maximum tensile residual stress is approximately 30% of yield stress and it is located close to weld centerline.

**Comparison between ACR and the cut compliance method**

Figure 6 shows the residual stress intensity factor profile obtained with the cut compliance method and the calculated residual stress distribution:

![Graph A](image1)

![Graph B](image2)

The general features and trends in the curves shown in Figures 6(A) and 6(B) are similar to those shown in Figures 4 and 5. There are some differences (mainly in the magnitudes of the measured quantities) between the ACR and cut compliance results that could result from several different factors. The cut compliance testing was carried out for a cutting direction from the retreating side to the weld centerline while the fatigue crack growth test (and consequently the ACR residual stress intensity determination) was performed for a crack growing from the advancing to the retreating sides. Also, the specimens used for the two tests were of necessity removed from different portions of the weld. It has not yet been established how the residual stress may vary from point to point in a titanium friction stir weld although unpublished research indicates that the measurements are very repeatable in aluminum welds. The overall good agreement is due to the fact that both techniques evaluate the residual stress intensity factor from a compliance measurement through the thickness and both methods perform a measurement of displacement caused by the progressive extension of a cut or crack.

**Conclusions**

In this paper it has been shown that the on-line crack-compliance combined with the ACR method is a practical technique for evaluation of the residual stress effects during a fatigue test of a FSW joint in titanium alloy. The methodology evidences the simplicity of both techniques to evaluate the residual stress intensity factor, $K_{res}$, and to separate the closure effect from the effective residual stress intensity factor range, $\Delta K_{eff}$. Moreover, the method does not require the knowledge of the influence functions and a specific test for determination of the residual stresses is not needed because their effect is directly obtained during the fatigue test.

Negative values of $K_{res}$ have been found outside the FS welded zone. The longitudinal residual stress distribution has been analytically extrapolated from the residual stress intensity profile through a closed inverse integral solution. Low crack growth rate outside the weld zone has been determined to be caused by the compressive residual stresses. Finally, a comparison between the on-line crack-compliance and the cut compliance techniques has shown a good agreement of $K_{res}$ profiles. Such a result has shown that the mentioned methodology can be used to evaluate the residual stress effect on the crack growth behavior of a FSW joint during a fatigue test.
References


