A TEST METHOD TO MEASURE THE EFFECTS OF RESIDUAL STRESS DURING AN FCG TEST

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Abstract
Residual stress in material can pose significant challenges during material characterization, especially during fatigue crack growth testing at relatively low values of applied ΔK, where even modest amounts of residual stress can bias the crack growth rate data. This paper discusses a recent test method that can be used during standard compliance-based fatigue crack growth testing to measure the stress-intensity factor, K_{res}, caused by the residual stress in a test specimen. This data can then be used to partition residual stress effects from the fatigue crack growth data, a necessary step to understand true material performance before introducing residual stress formally into the structural design process. Positive results have motivated an effort to standardize the method as a non-mandatory appendix in ASTM E647.

1. Introduction

Residual stress (RS) has long posed challenges during material characterization for a variety of material product forms, such as forgings, thick plate, extrusions, castings, weldments, and more recently additively manufactured material. These challenges emerge especially for fracture mechanics based testing such as fatigue crack growth (FCG) and fracture toughness characterization. RS can bias the resulting FCG or fracture toughness data, leading to incorrect assumptions about material performance. During material development, bias in the data can lead to an overly optimistic view of benefits or lead to promising concepts unnecessarily cancelled. Bias in design qualification data can lead to overly conservative or unconservative design data that will not transfer correctly to a full structure due to differences in stress redistribution in the structure versus a characterization coupon. A rigorous characterization process requires that residual stress effects be partitioned from the test data to reveal the true material performance, enabling design analysis to reintroduce residual stress formally as a structural loading condition.

Various options for managing residual stress in coupons have been used over the years, e.g. i) measure the RS nondestructively in the coupon using high energy synchrotron [expensive and/or high lead time]; ii) measure the RS in a companion specimen destructively [not necessarily the same stress field], but none provide an economical way to measure the RS effects in a reliable production setting directly on a coupon tested for characterization. This paper summarizes research performed to validate the crack compliance method to directly measure the stress-intensity factor, K_{res}, caused by the residual stress in a test specimen during an FCG test [1]. The method is a natural extension of a compliance-based method used for many years to measure crack length during a fatigue crack growth test, as defined in ASTM E647 "Standard Test Method for Measurement of Fatigue Crack Growth Rates."

A number of validation tests have been performed in recent years demonstrating the characterization process to partition residual stress effect from material data [2]. One such result is included here. Fatigue crack growth testing was performed using the compact specimen, C(T), for a crack growing through-thickness (L-S loading orientation) of a thick 7050-T7x51 plate that was known to have lengthwise residual stress (see Fig. 1). During the test, compliance was monitored according to the methods of reference 1. The testing was performed in a servo hydraulic loading frame using constant $K_{\max}$ = 10 ksi√in, constant stress ratio R = K_{min}/K_{max} = 0.1, frequency 10 Hz, in laboratory air. For comparison, Schindler's slitting method [4] was used on a duplicate specimen where a notch was introduced incrementally and strains at the back face ahead of the notch used to calculate the stress-intensity factor due to residual stress.

2. Results

Fig. 1 contains a plot of the stress-intensity factor due to residual stress, K_{res}, for duplicate FCG tests (filled symbols) and one slitting test (open symbols). The K_{res} from FCG is in remarkable agreement with each other and with that from slitting over a wide range of crack length (about 0.25 < a/W < 0.85). There is some variability in both the FCG and slitting data, but the variability is similar in both cases and small in comparison to the measured value of K_{res}. When residual stress is present, the crack tip stress-intensity factor can be very different from the applied value in the far-field of the specimen. ASTM E647 assumes linear elastic fracture mechanics, which means superposition is consistent with E647 (that is, for crack tip residual stress effects $K_{total} = K_{applied} + K_{res}$). At a crack length of a = 2 in. the crack tip stress ratio would be R = $K_{min\text{-}total}/K_{max\text{-}total}$ = (1 – 2)/(10-2), or R = -0.13. Thus, while the applied stress ratio is R = +0.1, at a crack length of a = 2 in. the crack tip stress ratio is R = -0.13. This would be expected to cause additional crack closure beyond what would be present for the applied stress ratio and to bias (suppress) crack growth rate data.

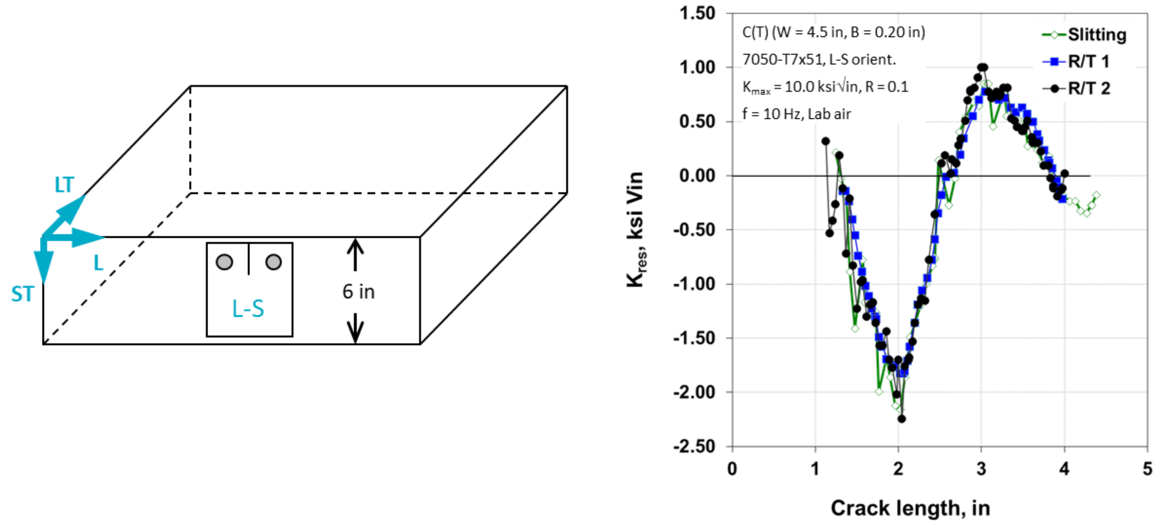

Fig.1 – Comparison of K_{res} determined from the slitting method with results from the current crack compliance method for thick plate material with specimen in the L-S orientation.

The positive results above, in addition to others [2], have motivated an effort to standardize the method as part of test method ASTM E647.

3. Conclusions

The crack compliance method of measuring the effects of RS on a test specimen provides a new and very useful tool for partitioning RS effects from property data for fracture mechanics based test data such as FCG data. In the past, the only methods for measuring RS on the actual FCG specimen required special resources, were expensive or had a long lead time (such as neutron diffraction). This new method enables measuring RS effects directly on the FCG specimen in real time during the FCG specimen, and thus requires no assumptions about residual stress variability from one specimen to the next. Standardization is in progress within ASTM E647.

References

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