ACCOUNTING FOR RESIDUAL STRESS IN FATIGUE CRACK GROWTH RATE TESTS: VALIDATION OF RESIDUAL STRESS INTENSITY FACTOR MEASUREMENTS

Christine M. Smudde[1], Jeffery C. Gibeling[1], and Michael R. Hill[2*]

[1]Department of Materials Science and Engineering, University of California, Davis, USA
[2]Department of Mechanical and Aerospace Engineering, University of California, Davis, USA
** Presenting Author email: mrhill@ucdavis.edu*

Abstract

Fatigue crack growth rate (FCGR) test data are a key to ensuring structural safety by design and inspection, but residual stress in test specimens can lead to significant (and unknown) bias in FCGR data. In turn, biased FCGR data confound estimates of structural capability for fielded systems. The paper will describe an experimental method for measuring the residual stress intensity factor as a function of crack size, $K_{res}(a)$, during FCGR tests and provide data for validation. Further test data show that simultaneous measurements of FCGR and $K_{res}(a)$ enable residual stress bias to be removed from FCGR test data.

1. Introduction

A set of FCGR test specimens was prepared, having been removed at specific locations from a bar of high-strength aluminum alloy in a state of elevated residual stress. The test material was obtained as 102 mm (4 inch) thick 7050-T7451 rolled aluminum plate that had been stress relieved by plastic stretch; stretched plate has low residual stress on the order of 20 MPa [1]. Bars cut from the plate, being 310 mm long (L), 76.2 mm wide (LT), and 102 mm thick (ST), were reprocessed to T74 temper, without the stretch to leave the bars with high residual stress on the order of 200 MPa [1]. A set of compact, C(T), specimens was machined from two blocks cut from one bar (here called B1 and B2), each specimen removed at a specific distance from the mid-thickness (Figure 1). Prior work had shown that specimens so prepared had a range of residual stress, with those taken near the bar mid-thickness having greater residual stress [2].

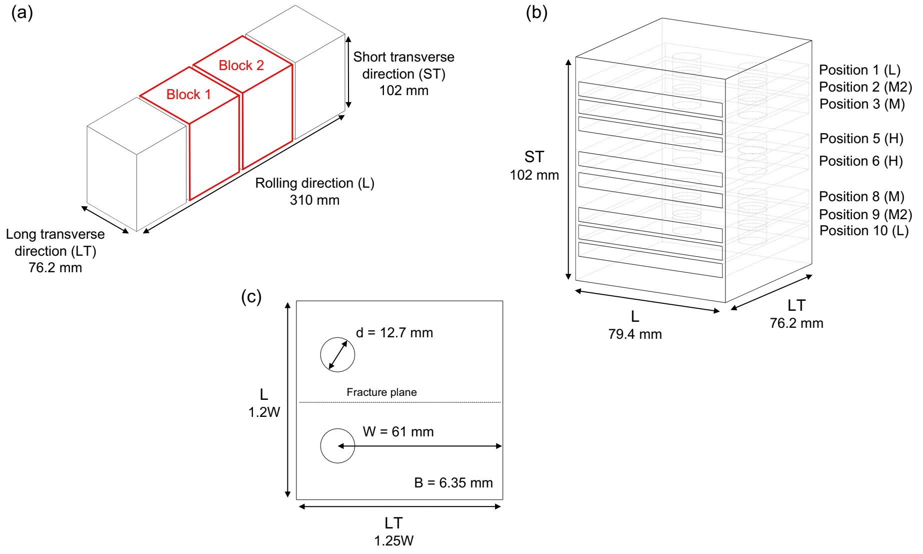

Figure 1: (a) Bar geometry with extraction of Block 1 (B1) and Block 2 (B2), (b) Block geometry with extraction of specimens and positions labeled, and (c) C(T) specimen geometry.

Validation of $K_{res}(a)$ measurement was performed by comparing results of two related experimental techniques. A first technique was slitting [1], which was performed in a laboratory using precision machining and metrology to determine the opening stress across the C(T) fracture plane. Slitting used wire electric discharge machining to cut the C(T) from the front face toward the back face (left to right in Figure 1(c)), with the cut completed in 50 increments of equal cut depth. A strain gage installed on the C(T) back face was used to record back face strain as a function of cut depth, BFS(a). The BFS(a) data were used in an elastic inverse analysis to compute residual stress as a function of position across the fracture plane that existed prior to the cut; a separate data analysis provided $K_{res}(a)$ from the same BFS(a) data. Data from slitting were compared to $K_{res}(a)$ determined during FCGR tests using a second technique known as on-line crack compliance, OLCC. OLCC relies on the same physical principal as slitting, with crack extension occurring by fatigue crack growth under cyclic loading and determining $K_{res}(a)$ from the evolution of BFS data with crack size. Significant prior work (e.g., [3]) established OLCC from the slitting technique [4] and recent work has provided additional description of the data analysis and also validation data [5].

2. Results

Residual stress data from slitting of C(T) specimens show similar shapes of the residual stress profiles for a range of specimens (Figure 2(a)) with the highest magnitude (H) in specimens removed near the block mid-thickness at positions 5 and 6 (specimens B1-5 and B2-6), the lowest magnitude (L) in a specimen removed near the block outer surface at position 1 (B1-1), and an intermediate level of stress (M) in a specimen removed midway between position 1 and 5 at position 3 (B1-3).

The values of $K_{res}(a)$ from slitting of C(T) specimens (Figure 2(b)) show the potential effect of the residual stress distributions (Figure 2(a)) on FCGR, where negative $K_{res}(a)$ would decrease R_{tot} relative to R_{app} and decrease FCGR. The similarity in shape of the $K_{res}(a)$ profiles for all different specimens is consistent with the similarity in shape of the residual stress profiles. The different magnitudes of $K_{res}(a)$ are consistent with the different magnitudes of residual stress.

$K_{res}(a)$ determined by OLCC during FCGR tests compare favorably to data from slitting. The level of data agreement is similar for samples with different levels of residual stress (L, M, or H) and gathered under different types test load control (ΔK constant, decreasing, or increasing). For tests under ΔK increasing (Figure 3(d)), $K_{res}(a)$ data depart the expected trend of $K_{res}(a)$ toward zero at longer crack sizes ($a \gtrsim 35$ mm; $a/W \gtrsim 0.57$), which was attributed to plasticity; at this crack size the estimated plastic zone size (r_p) is 5% of the remaining ligament and, with ΔK increasing, r_p increases rapidly with further fatigue crack growth.

3. Conclusions

The OLCC technique reflects a significant opportunity for removing residual stress bias from FCGR measurements. The validation data reported above show the agreement between OLCC and slitting to be within about ± 1 MPa $m^{0.5}$. The presentation will further provide FCGR data gathered along with the $K_{res}(a)$ data reported above and describe the removal of residual stress bias that allows measurement of intrinsic FCGR data free of residual stress bias. Simultaneous measurements of FCGR and $K_{res}(a)$ have been performed in a range of material systems to assess the utility of incorporating residual stress when interpreting FCGR data. Notably, using superposition to account for the effect of residual stress on the

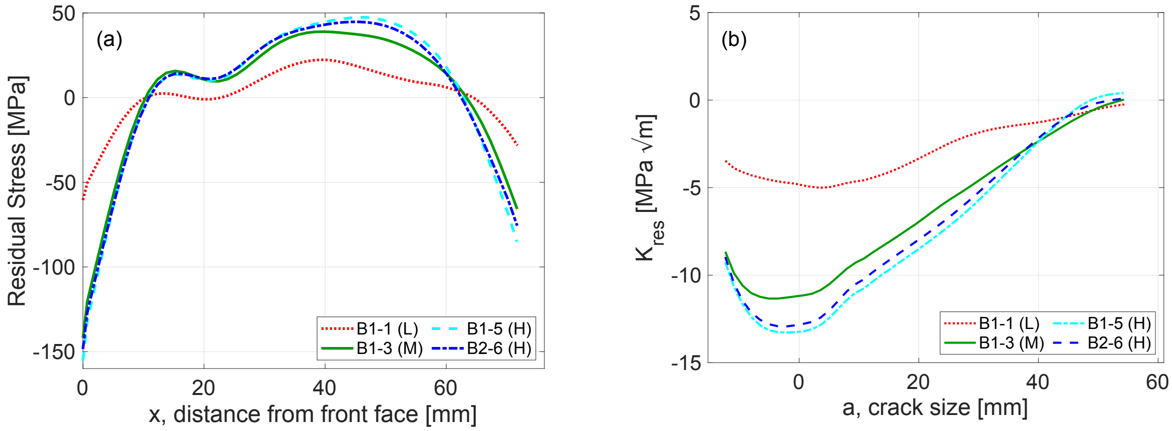

Figure 2:Data from slitting of C(T) specimens (without a notch): (a) residual stress and (b) $K_{res}(a)$ (note: x is measured from the front face while a is measured from the load line

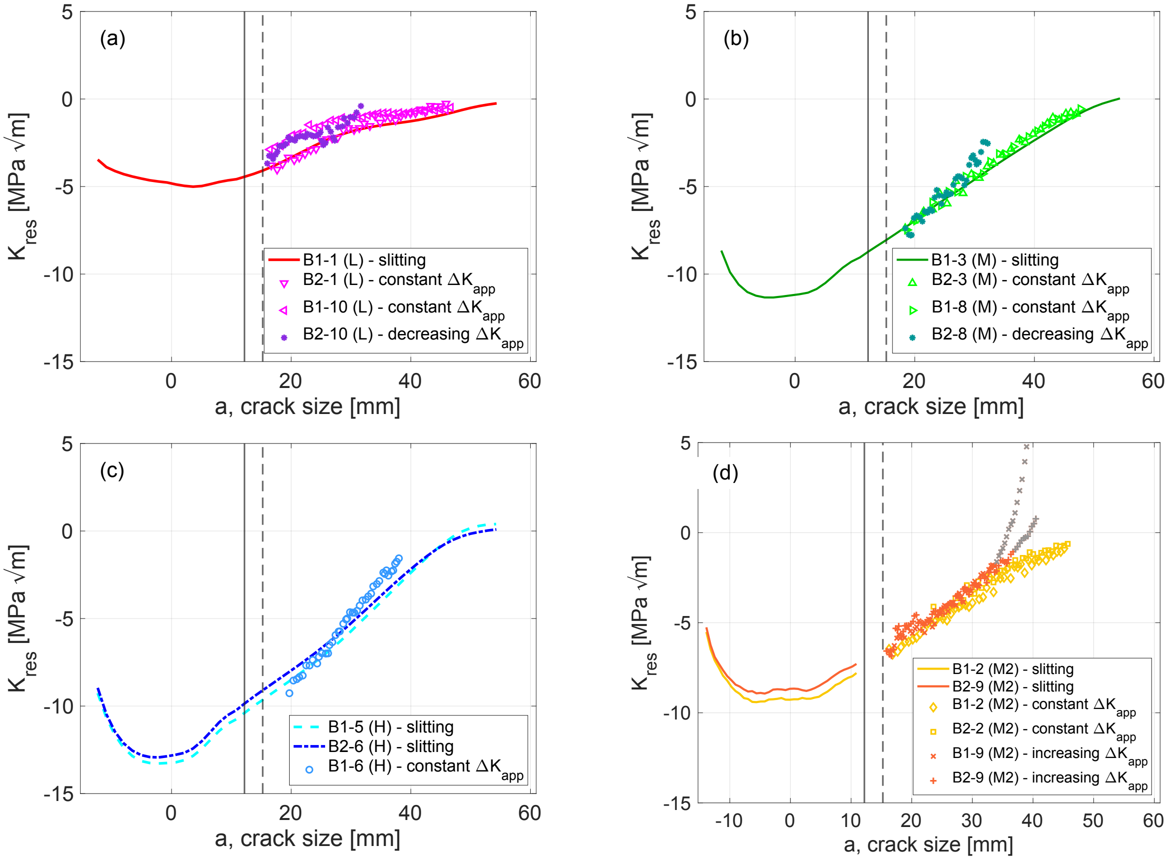

Figure 3:Comparison of $K_{res}(a)$ for specimens in replicate condition by slitting and OLCC for a range of residual stress level and type of FCGR test control: (a) low residual stress (L), (b) medium residual stress (M), (c) high residual stress (H), and (d) a second medium condition (M2) with stress between L and M; data in (d) from B1-9 and B2-9 shown in grey after a ≈ 35 mm are invalid due to plasticity

overall stress intensity factor ratio can provide a more useful comparison of related material conditions, such as when comparing FCGR in specimens from conventional, stress relieved wrought metallic product to FCGR in specimens with welds or removed from additive manufacturing builds.

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