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Predicting crack growth in specimens with overloads and cold-worked holes with residual stresses

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ABSTRACT

The FASTRAN life-prediction code was used to predict crack growth in specimens with compressive residual stresses on two aluminum alloys. All test data were obtained from the literature on middle-crack-tension or on specimens with a single through crack at an open hole. Specimens tested by Liu induced residual stresses by remote overloads, whereas the specimens tested by LaRue induced residual stresses by cold-expansion of the hole. Some modifications were made to FASTRAN to improve the residual-stress distribution and to simulate reaming of cold-worked holes. Overloads of specific magnitudes were applied to the FASTRAN strip-yield model to generate residual stresses that simulate those calculated from finite-element analyses from the literature. FASTRAN was then used to make fatigue-crack-growth predictions under residual-stress fields that compared fairly well with test results from the two aluminum alloys.

1. Introduction

The application of overloads on cracked structural components or cold-worked holes in structural joints induce compressive residual stresses at the crack fronts or at the edge of holes. These compressive residual stresses greatly enhance the fatigue crack growth characteristics (crack growth retardation) and increase the fatigue life of these components. In the past, elastic superposition methods have been used in crack growth models to account for these effects. However, this approach assumes that the residual-stress field is unaffected by crack growth and loading history. Because crack growth involves severe plastic deformations around the crack fronts and plastic deformations along the crack surfaces, there is a possibility that the compressive residual-stress fields may diminish as the crack grows through the plastic region caused by the overload or cold working, thus negating some of the benefits of the residual stresses. Also, under large compressive residual stresses, the maximum and minimum stress intensity factors may both be negative. Thus, the elastic superposition method may have difficulty in predicting the growth of cracks under these conditions.

The primary objective of this study was to enhance the FASTRAN crack-closure model [1–3] to simulate the introduction of compressive residual stresses due to cold-worked holes. The crack-closure model was initially developed in the late 1970's to predict crack growth during variable-amplitude load spectra [4], which models the plastic deformations and residual stresses during changing load histories, such as after an overload. Thus, overloads may conveniently be used to simulate the plastic deformations that are generated during the process of cold-working holes. The cold-working process plastically

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Nomenclature

a	crack length measured from edge of hole (mm)
a_i	initial crack length measured from edge of hole (mm)
B	thickness (mm)
c	crack half-length (mm)
D	hole diameter (mm)
F	boundary correction factor
K	stress-intensity factor (MPa m$^{1/2}$)
N	cycles
R	stress ratio ($S_{\min}/S_{\max}$)
r	hole radius (mm)
r_m	hole radius after reaming (mm)
S	remote applied stress (MPa)
$S_{\max}$	maximum applied stress (MPa)
$S_{\min}$	minimum applied stress (MPa)
S_{OL}	applied overload stress (MPa)
S_{op}	crack opening stress level (MPa)
w	one-half width of specimen (mm)
α	tensile constraint factor
β	compressive constraint factor
ΔK	stress intensity factor range (MPa-m$^{1/2}$)
ΔK_{eff}	effective stress intensity factor range (MPa m$^{1/2}$)
$(\Delta K_{\mathrm{eff}})_{\mathrm{T}}$	effective stress intensity factor range at flat-to-slant transition (MPa m$^{1/2}$)
δ	remote applied displacement (mm)
ρ	plastic-zone size (mm)
σ_{o}	flow stress (average of yield and ultimate tensile strength) (MPa)
σ_{rs}	residual stress (MPa)
σ_{ys}	yield stress (MPa)
σ_{u}	ultimate tensile strength (MPa)
ω	cyclic plastic-zone size (mm)

overloads the material around the hole by inserting a mandrel of slightly larger diameter than the original hole diameter, thus, plastically deforming the material concentrically around the hole. Once the mandrel is removed, a compressive residual stress develops at the edge of the hole due to the elastic material surrounding the hole. This is the same mechanism that causes plastic deformations, crack closure, and compressive stresses to develop at the crack front and along the crack surfaces.

Fatigue crack growth rate data generated on specimens with various forms of compressive residual stresses on two aluminum alloy materials (2024-T351 and 7075-T6) were studied. All test data analyzed herein were from the literature and were conducted on specimens with a single crack emanating from an open hole. The 2024 alloy test data was generated by Liu [5,6], and the 7075 alloy test data was generated by LaRue [7]. Liu conducted two types of tests on specimens with a central hole. First, Liu subjected the specimen to a very high overload (2/3 of the material tensile yield stress), cut an electron-discharge machine (EDM) slot into one side of the hole, and then subjected the specimen to constant-amplitude loading. Second, Liu cut an EDM slot into one side of the hole, fatigue precracked the specimen to obtain a crack of a specified length, subjected the specimen to the very high overload, and then subjected the specimen to constant-amplitude loading. LaRue [7] tested specimens made of 7075-T6 thin-sheet material with a central hole that had been cold worked (4.5%), reamed, and slotted with a small notch (0.25 mm in length). The specimens were then subjected to constant-amplitude loading.

The specimens tested by Liu induced compressive residual stresses by a remote overload, whereas the cold-worked hole specimens tested by LaRue induced residual stresses by pressure loading in the hole. Elastic–plastic finite element analyses of the cold-working process [7] were used to generate residual stresses around the open hole before and after reaming the hole. Overloads of specific magnitudes were then applied to the FASTRAN model to generate residual stresses that simulate those calculated from the finite element method. Comparisons were made between residual stresses calculated from both the finite element method and the crack-closure model. FASTRAN was then used to make fatigue crack growth predictions under the various residual-stress fields. Predictions made by the improved FASTRAN model were compared with experimentally measured fatigue crack growth behavior under the prescribed residual-stress fields.

2. FASTRAN life-prediction code and model

The FASTRAN life-prediction code has been successfully used to predict the fatigue crack growth lives for a wide variety of materials under a wide range of load histories (constant-amplitude and spectrum loading), see Refs. 8–13. Using the baseline