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Numerical predictions and experimental measurements of residual stresses in fatigue crack growth specimens

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ABSTRACT

Controlling macro residual stress fields in a material while preserving a desired microstructure is often a challenging proposition. Processing techniques which induce or reduce residual stresses often also alter microstructural characteristics of the material through thermo-mechanical processes. A novel mechanical technique able to generate controlled residual stresses was developed. The method is based on a pin compression approach, and was used to produce well-controlled magnitudes and distributions of residual stresses in rectangular coupons and compact tension specimens typically used in fatigue crack growth testing. Residual stresses created through this method were first computationally modeled with finite element analysis, and then experimentally reproduced with various levels of pin compression. The magnitudes and distributions of residual stresses in experimental specimens were independently assessed with fracture mechanics methods and good correspondence was found between residual stresses produced using the pin compression and processing techniques. Fatigue crack growth data generated from specimens with low residual stresses, high residual stresses resulting from processing, and high residual stresses introduced through the new pin compression technique were compared and validated. The developed method is proposed to facilitate the acquisition and analysis of fatigue crack growth data generated in residual stresses, validate residual stress corrective models, and verify fatigue crack growth simulations and life predictions in the presence of residual stresses.

1. Introduction

Most methods of processing metallic materials leave entrapped residual stresses due to plastic deformation and volume changes during phase transformation of material. In structural materials, the effect of residual stresses on fatigue failure, fracture, and stress corrosion cracking has been of primary importance and interest. While many processes introduce beneficial compressive residual stresses that impede the initiation and growth of cracks, they also cause material and component variability if uncontrolled. Moreover, residual stresses create bias in data generation and interpretation leading to inaccuracies in structural design.

Determination of the residual stress magnitude, distribution, and re-distribution within rectangular testing coupons and the resulting effect on fatigue crack growth (FCG) has been studied [1–12]. To understand the effect on fatigue crack growth it is imperative to be able to control the magnitude and distribution of residual stresses while maintaining the material microstructure. Previous studies have investigated the introduction of surface residual stresses to common FCG and fracture

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Nomenclature

a	crack length (measured from the center of specimen loading holes in the case of the compact tension (C(T)) specimen geometry)
da/dN	crack growth rate as crack extension per cycle
b	total compact tension (C(T)) specimen width in the direction of crack growth
B, W	compact tension (C(T)) specimen thickness and width
d	vertical distance from the center of compact tension (C(T)) specimen loading pin holes to the mid-plane of the specimen
e%	elongation at failure
E	modulus of elasticity
h	half of total compact tension (C(T)) specimen height normal to the direction of crack growth
K_{res}	stress intensity factor due to residual stress
ΔK_{app}	applied stress intensity factor range
ΔK_{th}	crack growth threshold corresponding to a growth rate of 10^{-7} mm/cycle
ΔK_{FT}	stress intensity factor range at specimen failure
R	stress ratio
$d\delta$	change in front face displacement
Δ	total front face displacement
ν	Poisson's ratio
σ_{res}	residual stress
σ_{UTS}	ultimate tensile strength
σ_Y	yield strength determined by 0.2% offset technique
$A_{\nu u}$	coefficient matrix used in conjunction with fracture mechanics approaches and specimen weight functions to calculate residual stress
$h(x,a)$	geometry dependent weight function used in the calculation of residual stress from fracture mechanics approaches
$Z(a)$	geometry dependent influence function used in application of the cut compliance technique

toughness testing geometries using mechanical techniques to replicate residual stresses produced from processing [3]. Mechanical methods are advantageous when introducing surface or bulk residual stresses since they do not induce changes in microstructure in most structural materials.

The accurate interpretation and analysis of FCG and fracture toughness data rely on the knowledge and correction of residual stress effects in models and simulations. Residual stress in rectangular coupons has been measured by strain relaxation during incremental cutting [7–9]. The cut compliance technique, a linear-elastic fracture mechanics approach, is convenient due to its direct applicability to the correction of FCG data generated from specimens with similar residual stress distributions and magnitudes, but is limited to specific geometric configurations. Recently crack compliance techniques have been developed to calculate the stress intensity due to residual stress at the crack tip, K_{res}; this method can be conveniently incorporated into real-time data collection tools [12].

The current work proposes an original methodology to mechanically introduce various magnitudes and distributions of residual stresses into compact tension (C(T)) specimens by the compression of pins inserted at select locations. In this study, the stress magnitude and distribution was tailored and optimized to match that produced by a cold water quench, a common heat treatment process. The method to create the desired stress distribution in C(T) specimens was optimized through a succession of analytical and numerical models. An experimental replica of the final numerical model was created and residual stress levels were evaluated using the cut compliance method, a fracture mechanics technique [7,9]. FCG testing was performed on C(T) specimens of low and high quenching residual stresses and high pin compression residual stresses to compare crack growth behavior and validate the proposed pin compression methodology.

2. Modeling methodology

Numerical modeling was performed using ANSYS finite element analysis (FEA). A progressive analysis from 2D linear-elastic FEA to 3D elastic–plastic FEA including contact, through-thickness stress variation, and elastic spring-back after deformation was performed to predict residual stress profiles in C(T) specimens. 2D linear-elastic modeling was performed first to develop an optimized size and location of compression pins without the additional nodes and added computational time which would be required to model 3D elastic–plastic behavior.

2.1. 2D linear-elastic modeling

Numerical modeling was applied to the C(T) geometry, Fig. 1. A series of linear-elastic sensitivity studies in plane stress with thickness were conducted to determine the optimal pin size, location, and loading necessary to produce the residual