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Finite element crack closure analysis of a compact tension specimen

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Abstract

Crack closure behaviour of a compact tension (CT) specimen subjected to a constant amplitude cyclic mechanical load, with load ratio $R = -2$ and the maximum load approaching and exceeding the yield strength based limit load of the specimen, has been examined by performing large strain elastic–plastic finite element (FE) crack growth analyses assuming kinematic hardening. Results from static analyses show that the near crack tip stress and plastic strain fields do not change significantly with further loading after crack closure takes place. Results from crack growth analyses show that the crack closure type depends on the maximum stress intensity factor (SIF) and the crack tip constraint conditions, and that the crack opening/closing loads can be correlated by the maximum SIF, for given crack tip constraint conditions (plane stress/strain). The equation given in the R5 procedure for the crack closure factor, q_0, is conservative compared with the results obtained from the FE simulation.

Keywords: Fatigue crack growth; Crack closure; Finite element; Crack closure factor; Load ratio

1. Introduction

In order to assess the remaining life of power station components manufactured from austenitic Type 316H steel, a series of fatigue, creep and creep-fatigue crack growth tests have recently been performed by British Energy [1]. Among the tested specimens was a side-grooved compact tension (CT) specimen subjected to combined low cycle fatigue and creep loading at a temperature of 525 °C under a constant amplitude cyclic load. The maximum load 11 kN and load ratio, R, the ratio of minimum to maximum loads, was equal to –2. The maximum applied load corresponds to 0.64 and 1.28 times the yield strength based limit load of the specimen for the initial and final crack lengths, respectively. In the test, the maximum load was held for 96 h in each cycle, which resulted in creep crack growth. The test lasted 12 cycles and the pure fatigue crack growth rate obtained was between 0.028 and 0.16 mm/cycle. In order to understand how the extremely high compressive load affects the crack tip stress and strain fields and, therefore, the fatigue damage in the near crack tip region, and also to determine if the estimate of the crack closure factor, q_0, in the R5 high temperature assessment procedure [2] still applies, detailed 2-D finite element (FE) analyses for this CT specimen have been performed. Crack closure behaviour during crack growth under cyclic load was modelled. The CT specimen was analysed under constant amplitude triangular waveform loading without the dwell period because only the crack closure behaviour under cyclic loading was of concern to this investigation.

Many factors could contribute to crack closure during fatigue crack growth tests [3]. However, the specimen considered was tested under low cycle fatigue conditions and plasticity-induced crack closure is expected to dominate. Therefore, only plasticity induced crack closure is considered in this paper. This effect is due to the plastic wake left behind the moving crack tip during fatigue crack growth. During loading, large tensile plastic strains are developed near the crack tip, which are not fully reversed upon unloading. This leads to the formation of a plastic wake

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Nomenclature

a	crack length
a_0	initial crack length
B	specimen thickness
C	material constant in fatigue crack growth law
da/dN	fatigue crack growth per loading cycle
E	Young's modulus
E_1	plastic modulus
$f(a/W)$	non-dimensional function of a/W for K evaluation
K	mode I stress intensity factor
K_{min}	K corresponding to P_{min}
K_{max}	K corresponding to P_{max}
K_{op}	K corresponding to P_{op}
ΔK	stress intensity factor range, $=K_{max} - K_{min}$
ΔK_{eff}	effective stress intensity factor range, $=q_0 \Delta K$
l	notch length
m	exponent in fatigue crack growth law
N	number of loading cycles
P	load
P_{cl}	load corresponding to crack closing point
P_{max}	maximum load in a cycle
P_{min}	minimum load in a cycle
P_{op}	load corresponding to crack opening point
P_L	limit load
ΔP	load range, $=P_{max} - P_{min}$
q_0	crack closure factor
R	load ratio, $=P_{min}/P_{max} = K_{min}/K_{max}$
r	distance from crack tip, polar co-ordinate
W	specimen width
x, y	Cartesian co-ordinates
β	constant for the crack tip plastic zone size, $=6$ for plane strain and $=2$ for plane stress
ε	strain
ε^p	plastic strain
ε^p_{yy}	y-direction plastic strain along the crack ligament
ε_y	yield strain, $=\sigma_y/E$
ν	Poisson's ratio
σ	stress
σ_y	yield stress or 0.2% proof stress, normalising stress
σ_{yy}	y-direction stress along the crack ligament

behind the crack tip and subsequently reduces the driving force for fatigue crack growth.

Plasticity-induced crack closure has been one of the most widely studied research topics in the area of fatigue crack growth since it was observed and reported by Elber [4]. Many researchers have simulated plasticity-induced fatigue crack closure using the 2-D FE method (e.g. [5–22]). The key issues addressed included mesh refinement [9,10,15,18,21,22], crack face contact [5,7,9,13,15,18,19], crack advance method [6,9,13,15,18], the methodology for determining the crack opening load [5,11,13,17,19] and the stabilisation of the crack opening load [5,13,18,21]. General reviews have been presented by McClung [23], Newman [24] and Solanki et al. [25]. Many researchers have also performed crack closure analyses for CT specimens, e.g. [7,11,15–20,22]. For example, Blom and Holm [7] simulated the fatigue crack closure of a CT specimen in aluminium alloy. However, the mesh used in the research was quite coarse. Sehitoglu and Sun [11] analysed the fatigue crack closure of plane strain and plane stress CT specimens for $R = 0.3$, 0 and -1 under various maximum load levels. In their study, the crack tip stress was first used to determine the crack opening load. Dougherty et al. [15] simulated fatigue crack growth tests on CT specimens [14] under plane strain conditions and demonstrated a good comparison with the experimental results. Ashbaugh et al. [16] simulated the fatigue crack closure of CT specimens used in their aluminium–copper alloy fatigue crack growth. However, only 4–5 elements were located in the forward plastic zone ahead of the crack tip. The mesh refinement was clearly less than the minimum requirement proposed by McClung and Sehitoglu [9]. Wei and James [17] simulated the fatigue crack closure of polycarbonate CT specimens under plane strain and plane stress conditions for $R = 0.5$, 0.25, 0 and -0.5. They studied two approaches for determining the opening load, namely the crack face contact method [5] and the crack tip stress method [11,13], and found that the opening load obtained from the crack face contact method was in good agreement with that measured experimentally. Solanki et al. [18,19] performed fatigue crack closure analyses of a CT specimen under both plane strain and plane stress conditions for $R = 0$ at a very low maximum load level to study the effect of mesh refinement. They found that, for plane strain conditions, the opening load did not converge with increasing mesh refinement [18]. They also developed a new method [19], the crack face contact stress method, for determining the crack opening load. Gonzalez-Herrera and Zapatero [22] also performed fatigue crack closure analyses for a CT specimen to study the mesh refinement issue and obtained a conclusion similar to Solanki et al. [18]. Zhao et al. [20] performed fatigue crack closure analyses of a CT specimen with both plane stress and plane strain conditions under a very low load level for $R = 0$ and for various material properties.

The cases analysed in [5–22] correspond to different R values, maximum load levels, material properties and crack lengths and are not easily compared. Moreover, no analysed case for the CT specimen has been found to address fatigue crack closure for a load ratio $R = -2$ at a maximum load level close to the limit load of the specimen. In this paper, 2-D crack growth simulation is described for