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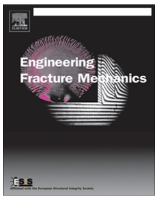

A study of overload effect on fatigue crack propagation using EBSD, FIB–DIC and FEM methods

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ABSTRACT

Abrupt increase in the maximum load during fatigue cycling modifies the deformation conditions at the crack tip, causing plastic flow that may lead to crack closure, introducing residual stress and hardening. The net consequence of these effects is notable crack growth retardation. Despite decades of research in the field, controversy persists regarding the role of each specific mechanism and their interaction. Resolving these issues with the help of experimental observation is related to the difficulty of obtaining local residual stress information at appropriate resolution. The present study examines the effect of overload on fatigue crack grown in a Compact Tension (CT) specimen of aluminium alloy AA6082 (BS HE30). Fatigue crack was grown in the sample under cyclic tension ($R = 0.1$). After the application of a single overload cycle, fatigue loading was recommenced under previous cycling conditions. The crack morphology was investigated using Scanning Electron Microscopy (SEM). Electron Backscattered Diffraction (EBSD) was used to map grain orientation and crystal lattice distortion (pattern quality) in the vicinity of the crack. EBSD analysis of intra-granular misorientation allowed the qualitative analysis of the region around the crack tip location at the time of the overload application. Observations are discussed with a view to identify the roles of crack closure and residual stress effects. Residual stress was evaluated at salient locations around the crack retardation site using the FIB–DIC method which combines the use of Focused Ion Beam (FIB) and Digital Image Correlation (DIC) for residual stress measurement at the (sub)micron-scale. The residual stress field due to overload occurrence was also simulated using Finite Element Method (FEM), and the results compared with experimental observations.

1. Introduction

Variable amplitude fatigue is a common loading mode for mechanical components in service. To optimise the reliability of engineering components under variable amplitude, the crack growth rate needs to be quantified and fatigue life estimated. The fatigue crack growth rate (FCGR) is affected by the plastic deformation at the crack tip, caused by the remote load application. However, the correlation between the loading spectrum and the fatigue life is complex and may sometimes appear counter-intuitive. To elucidate the effect of external load variation on crack growth, the effects of an elementary occurrence of a single overload (OL) or underload (UL) are often examined [1,2]. Generally, underload (UL), i.e. the

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Nomenclature

K_I	mode I stress intensity factor
ΔK	stress intensity factor range
F	applied force to the specimen
ΔF	cyclic force range
$F_{\min}$	minimum force applied to the specimen
$F_{\max}$	maximum force applied to the specimen
F_{OL}	overload force applied to the specimen
b	specimen thickness
W	specimen width
a	crack length
da/dn	fatigue crack growth rate
C	Paris' law intercept coefficient
m	Paris law slope coefficient
E	Young's modulus
v	Poisson's ratio
σ_{xx}	stress (*xx* component)
σ_{yy}	stress (*yy* component)
ε_{xx}	strain (*xx* component)
ε_{yy}	strain (*yy* component)
n	hardening exponent
K	strength coefficient

application of compressive load to the crack accelerates it, whilst overload (OL) leads to a retardation of the fatigue crack propagation. A quantitative measure of FCGR reduction due to the OL is the number of cycles that it takes for the crack to regain the original steady state growth rate. The retardation is related to all aspects of material structure and state change around the crack tip, and persists until the crack grows out of the region perturbed by the OL application. Immediately after the application of an OL, a very short acceleration of the propagation rate may be observed before the retardation sets in. This event appears especially when the OL ratio is greater than 1.5 ($R_{OL} = F_{OL}/F_{\max}$) with respect to the cyclic load maximum [2] and it is thought to be due the significant the damage induced by OL in the material surrounding the crack tip. The size of the plastic zone at the crack tip is one of the most important parameters that determines the conditions of its advancement. Further, variation in the specimen thickness changes the stress state within the sample and around the crack from being closer to plane stress or plane strain. Hence specimen thickness determines the overall apparent plastic zone size. Retardation or acceleration may depend not only on the UL or OL being applied, but also on the stress ratio. In fact, it has been shown [3] that in some cases a negative stress ratio in combination with an OL may cause acceleration of fatigue crack growth instead of the expected retardation. Furthermore, it has been shown that under negative load ratio the cyclic plastic properties of the material play an important role in determining the crack propagation rate.

The effect of retardation can be attributed to several mechanisms. In most cases an OL leads to crack blunting. Hence further crack propagation may require crack re-nucleation, with a consequent delay in crack growth.

Another mechanism, perhaps the most important to mention in the context of crack retardation, is the crack closure effect [4,5]. An OL causes plastic deformation at the crack tip, and produces excess material just ahead of it. Once the crack tip moves beyond this region, the crack flanks maintain contact causing the crack tip to be delayed, reducing the effective stress intensity factor range ΔK, and with it the crack growth rate.

Another often used explanation for crack retardation is the presence of residual stress at the crack tip [6,7]. The large plastic deformation at the crack tip induced by the OL generates compressive residual stress that induces crack retardation associated with either re-nucleation or slower propagation. At micro-scale the behaviour of small material volumes may be anisotropic, contributing to the variation in response between samples and locations [8]. The residual stress effect can be accounted in terms of the additional stress intensity factor terms acting locally at the crack tip [9]. The effect of crack tip shielding induced by plastic deformation can also be taken into account during fatigue endurance evaluation by means of the modified SIF or Weight Function method, as proposed in [10].

The knowledge of the local behaviour of the material at the vicinity of the crack tip therefore plays a crucial role in the problem of crack propagation and retardation. Hence, the evaluation of the stress–strain state that arises in the process zone is necessary. However, the small size of the plastic zone for materials of interest means that few techniques are available for the task. One such technique is micro-indentation [11] which can map mechanical properties at good special resolution, but is unable to deliver sufficient accuracy for residual stress evaluation. It has been reported [6,8,9] that, the use of synchrotron X-ray diffraction, allowed high-resolution mapping of the region of interest, including under *in situ* loading. An important advantage of the method being that it is truly non-destructive and non-invasive.