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Special criterion for crack path prediction at micro-structural scale based on dominate slip system and grain boundary

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ABSTRACT

This study develops a new method for the analysis of fatigue crack growth at micro-structural scale. Proposed model was constructed based on material anisotropic properties and crystallographic planes. In this research, it has been attempted to suggest an accurate and precise criterion for the prediction of crack growth path at micro-structural scales by the study of various criteria for crack growth. For this purpose, considering fracture energy for trans-granular and inter-granular fracture as well as dominant slip planes, a criterion was proposed to predict crack growth. In the current research, fatigue tests were performed on two different alloys and the real path of the crack growth was obtained. Next, by the simulation of tested pieces through finite element software (ABAQUS) and using extended finite element method, various criteria to predict crack growth path were studied. The microstructures of both specimens tested in considered areas were modelled with an anisotropic behaviour and their crystal orientations were gained using electron-back-scattering-diffraction-pattern (EBSP) method. The results suggest the accuracy and precision of proposed criterion with minor error in single-phase alloys and major difference in two-phase alloys.

1. Introduction

The material microstructure plays a pivotal role in dictating the modes of fracture and the macroscopic response of real materials. The grain morphology, elastic modulus, the toughness of the individual micro-structural constituents and interfaces and slip system are key parameters which control the failure mechanisms in poly-crystalline materials. Many researchers have reported the sudden change of the crack path and massive fluctuation in crack tip parameters such as J integral and ΔK_{eff} in their studies [1]. High percentage of these phenomena stems from micro-structural causes such as, anisotropic elastic properties of grains and grain boundary. Hence, thorough understanding of crack growth mechanism at micro-structural scales, the slip plane effects as well as the influence of grain boundary upon crack growth can be of outmost importance. Furthermore, it is worth to study and propose a criterion for the prediction of crack growth path and its rate.

Quasi-static crack propagation through a material microstructure depends on the mechanical state in the vicinity of the crack-tip; therefore, local differences in toughness (grain interior versus grain boundaries) affect the crack path, significantly. The crack path and propagation directions in the grain cannot be only predicted by the stress field, since cracking is restricted to distinct crystallographic planes. Telesman and Ghosn [2] and Chen and Liu [3] introduced a two-dimensional prediction method based on a resolved shear stress intensity parameter that represents the stress intensity on a specific crystallographic plane. Tinga studied the effect of slip system on crack path using the resolved shear stress intensity parameter, K_{rss} and then justified zigzag crack path in nickel super alloy [4]. In light of the above, it is clear that any numerical fracture model which is able to predict crack propagation by incorporating these micro-structural features, has the potential of describing toughening mechanisms in poly-crystals and can provide a framework for micro-structural design.

Yang et al. used the Potts grain growth model to generate a poly-crystalline microstructure which was mapped into a triangular lattice [5,6]. The mechanics of this structure was represented by a spring network on the lattice, where a spring fails if the stored elastic energy in the spring exceeded a critical value [7–10]. The transition from inter-granular (growth along the grain boundary) to trans-granular (growth inside the grain interior) fracture with the increase of grain boundary toughness was observed and the influence of thermal-mismatch on micro-cracking was studied [5].

A significant improvement in discrete crack modelling has been released with the development of the extended finite element method (X-FEM) [11]. In this approach, the domain is modelled by finite elements with no explicit meshing of the crack surfaces. The location of the crack discontinuity can be arbitrary with respect to the underlying finite element mesh and quasi-static

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Table 1
Compositions of nickel super alloy [1].

Element	C	Al	B	Co	Cr	Mo	Ta	W	Zr	Ti	Ni
wt.%	0.1	3.03	0.02	9.56	13.93	1.56	2.77	3.86	0.01	4.90	Bal.

simulations, modelling of fatigue crack propagation, can be performed without the need of re-meshing as the crack advances. In the X-FEM, a discontinuous function (generalised Heaviside step function) and the two-dimensional asymptotic crack-tip displacement fields are added to a standard displacement-based finite element approximation to take into account the presence of the crack using the notion of partition of unity [12,13].

Nickel super alloys and Two-phase α+β titanium alloys are used in a wide variety of aerospace applications (e.g. turbine-engines in commercial and military aircrafts) because they exhibit excellent fatigue crack propagation resistance, fracture toughness, creep resistance and low density. Nickel-based super alloys are used in both turbine disc and blade assemblies due to their excellent high-temperature properties. Thus, it is necessary to make detailed study of this alloy from the view point of increasing the fatigue crack propagation [1].

This study develops a new method for the analysis of fatigue crack growth at micro-structural scale. Proposed model was constructed based on material anisotropic properties and crystallographic planes. In this research, it has been attempted to suggest an accurate and precise criterion for the prediction of crack growth path at micro-structural scales by the study of various criteria for crack growth. For this purpose, considering fracture energy for trans-granular and inter-granular fracture as well as dominant slip planes, a criterion was proposed to predict crack growth. Fatigue tests were performed on two different alloys and the real path of the crack growth was obtained. Next, by the simulation of tested pieces through finite element software (ABAQUS) and using extended finite element method, various criteria to predict crack growth path were studied. The microstructures of both specimens tested in considered areas were modelled with an anisotropic behaviour and their crystal orientations were gained using EBSP method. The results suggest the accuracy and precision of proposed criterion with minor error in single-phase alloys and major difference in two-phase alloys.

Table 2
Anisotropic elastic constant of nickel crystal (cubic structure-FCC)[1].

Property	Value (GPa)
$C_{11}=C_{22}=C_{33}$	201.5
$C_{12}=C_{13}=C_{23}$	137.1
$C_{44}=C_{55}=C_{66}$	98.5

2. Materials and experiments

Several experiments were performed to study the crack path in two different alloys, the single-phase nickel super alloy and the two-phase titanium alloy. The nickel super alloy with single-phase and coarse grains is often used in high temperature parts of jet-engines because of its suitable creep properties. Table 1 shows the chemical composition of this alloy. The crystal lattice structure of the above-mentioned nickel super alloy is Face-Centred Cubic, FCC, and its anisotropic elastic constants are tabulated in Table 2.

A γ/γ' precipitation strengthened DS super alloy was machined into a crack-centred-plate specimen (Fig. 1a), and subjected to a load-controlled uni-axial cyclic loading [1]. Since DS axis was set to be perpendicular to the flat section of the specimen, the crack edge was aligned parallel to the DS axis, macroscopically, see Fig. 1b. The form of loading wave was triangular with the maximum/minimum stresses of 400 MPa and −200 MPa, respectively, with a frequency of 0.13 Hz [1].

Ti–6Al–4V is a common alloy used in low-temperature parts of jet-engines and it contains fine grains formed by two phases, α and β. The chemical composition of this alloy is tabulated in Table 3. The α phase of this alloy has HCP structure and its elastic properties are shown in the Table 4. The β phase of this alloy has lamellar structure of BCC and secondary α has HCP structure, as well. Furthermore, elastic properties in BCC structure of β phase are included in Table 5.

Table 3
Compositions of Ti–6Al–4V [14].

Element	C	N	Fe	O	Al	V	Ti
wt.%	0.1	0.05	0.3	0.2	6	4	Bal.

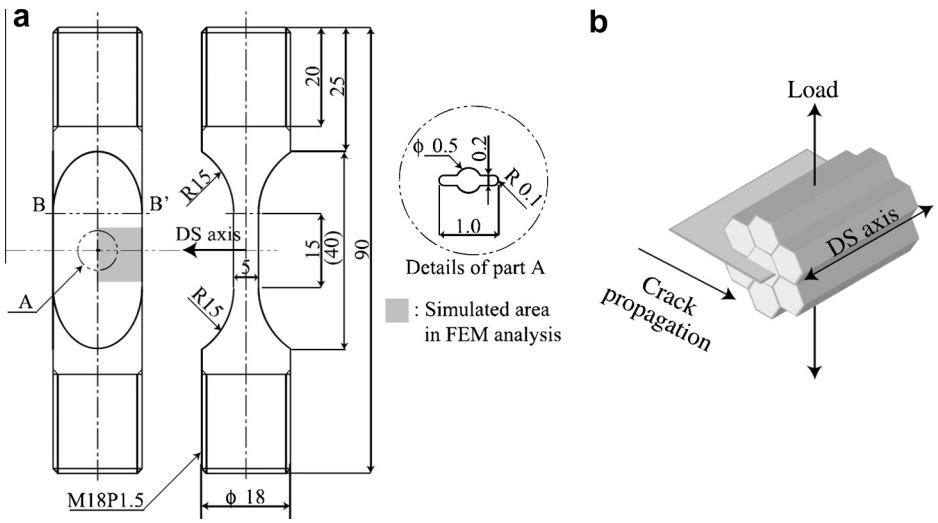

Fig. 1. (a) Geometry of centre-cracked plate specimen (mm) and (b) relative orientation of grains and crack path [1].