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Fatigue life prediction of nickel-based GH4169 alloy on the basis of a multi-scale crack propagation approach

Shen Ye[a], Cheng-Cheng Zhang[b], Peng-Yue Zhang[c], Xian-Cheng Zhang[a,*], Shan-Tung Tu[a,*], Run-Zi Wang[a]

[a] Key Laboratory of Pressure Systems and Safety, Ministry of Education, School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, PR China

[b] AECC Commercial Aircraft Engine Co. LTD, Shanghai Engineering Research Center for Commercial Aircraft Engine, Shanghai 201108, PR China

[c] Collaborative Innovation Center of Standardization and Intellectual Property Management of Zhejiang Province, Zhejiang 310018, PR China

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ABSTRACT

This paper was concerned with an approach to predict fatigue life based on a multi-scale crack propagation model. The expressions of crack propagation rates in microstructurally small crack (MSC), physically small crack (PSC) and long crack (LC) stages were unified in the multi-scale crack propagation model. Its integral form presented a fatigue life prediction approach. The nickel-based GH4169 alloy was employed to validate the prediction capacity of present approach. The prediction results of lives of specimens with different initial defects sizes were compared with the experimental data.

1. Introduction

Considerable amounts of failures in components and structures are caused by fatigue loadings. Fatigue damage is one of the most important factors which should be taken into consideration at the lifetime-designing stage for components and structures. As to the design criterion for damage tolerance based on the fracture mechanics methodology, usually the stage of crack nucleation is beyond consideration. A crack is assumed to exist in a component or a structure prior to its service while the criterion of maintenance interval depends on assessment of crack propagation rate [1]. Thus, a precise approach of predicting the fatigue propagation life ensures the safety and reliability of a structure.

Fatigue crack growth rate is conventionally evaluated based on principles of linear elastic fracture mechanics (LEFM). Stress intensity factor range, ΔK, which is defined as an elastic fracture-mechanics parameter under small-scale yielding conditions, is considered as the driving force for crack propagation and is correlated with crack growth rate by the Paris law at this scale. The propagation law described by LEFM has been validated in many different metallic materials. However, this approach also shows limitations. It is generally accepted that a fatigue crack experiences small crack stage and long crack stage before the final fracture occurs. Actually, it can be classified as microstructurally small crack (MSC) stage, physically small crack (PSC) stage and long crack (LC) stage [2,3]. Methods based on LEFM are invalid in the small crack stage since the micromechanics around the crack tip are not taken into account. It is found that small crack has a higher growth rate than long crack growth does at the same equivalent stress intensity factor range. Moreover, the small crack is able to propagate even below the long crack threshold. Investigations on small crack propagation were widely carried out [4–8] after Pearson discovered these anomalisms in aluminum alloy in 1975 [9]. A bunch of theoretical methods were proposed to model and predict the crack growth rate in such scale. Most of these methods were

* Corresponding authors at: Key Laboratory of Pressure Systems and Safety, Ministry of Education, Meilong Road 130, Xuhui District, Shanghai 200237, PR China.
E-mail addresses: xczhang@ecust.edu.cn (X.-C. Zhang), sttu@ecust.edu.cn (S.-T. Tu).

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Nomenclature

a	half surface crack length
a_0	initial defect or crack size
a_i	half surface crack length at N_i cycles
b	half width of specimen
C	coefficient of power function
c	crack depth
D	average grain size
d	critical size
E_{coh}	cohesive energy
F	boundary-correction factor
ΔK	nominal stress intensity factor range
ΔK_{th}	long crack threshold of stress intensity factor range
ΔK_{ths}	short crack threshold of stress intensity factor range
ΔK^*	modified stress intensity factor range
k_y	material constant in Hall-Petch relationship
N	number of cycles
N_{INI}	number of cycles spending on crack initiation stage
N_{MSC}	number of cycles spending on microstructurally small crack stage
N_{PSC}	number of cycles spending on physically small crack stage
N_{LC}	number of cycles spending on long crack stage
n	exponent of the power function
Q	shape factor
q	correction factor
R	stress ratio
r_{pc}	cyclic plastic zone size
t	thickness of parallel section
α	transition factor
$\Delta\sigma$	applied stress amplitude
$\sigma_{\max}$	maximum stress
σ_y	macroscopic yield strength
σ_y^m	local yield strength
σ_0^m	initial value of local yield strength
σ_{fl}	fatigue limit
φ	angular function
γ_B	surface energy

Abbreviations

MSC	microstructurally small crack
PSC	physically small crack
LC	long crack
LEFM	linear elastic fracture mechanics

developed from the perspective of microstructural effect or crack tip plasticity. For example, Hobson proposed a simple power function to model the crack growth behavior inside of a grain and the retardation of growth rate induced by the grain boundary [6]. The concept of microstructurally dissimilitude was developed by Chan and Lankford to describe the small crack propagation [10]. Shyam et al. quantitatively assessed the crack tip plasticity and proposed a linear relation with monotonic and cyclic displacements [11]. Referring to multi-scale crack propagation model, some theoretical approaches were proposed based different classifications [12–15]. However, the issues of anomalism in the MSC propagation were still not thoroughly solved.

Some crack propagation models are utilized in predicting the fatigue life by integrating the predicted growth rates. For example, Newman et al. developed a plasticity-induced crack closure model to predict the long crack propagation behavior and generalized it to small crack stage [16]. Santus et al. unified the expression of crack growth rate at the PSC stage and LC stage by replacing the term of long crack threshold with small crack threshold in the LC model [2]. However, most of these methodologies are obscure at the small crack stage, especially at the MSC stage. Since the small crack has a higher and more randomly propagation rate than the LC does at the same nominal ΔK, the predicted life, i.e. the integration of crack growth curve, only based on LC model produces a non-conservative prediction result, which is dangerous in engineering cases. With the development of detecting techniques, the detectable initial defect size in critical component decreases. Thus, there is a pressing requirement for a lucid method to uniformly predict multi-scale crack propagation from the MSC, the PSC and the LC stage.

A multi-scale crack propagation model unifying the expression of crack growth rate in MSC, PSC and LC stages, had been developed in our previous work [17]. The aim of this paper was to provide a fatigue life prediction method based on such model in

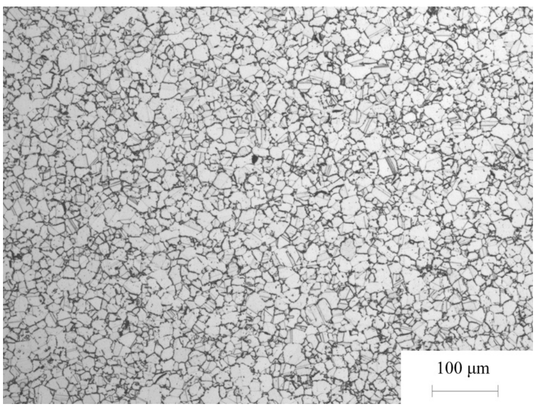

Fig. 1. Microstructures of alloy GH4169 after solution heat treatment.