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Grain size effect on the small fatigue crack initiation and growth mechanisms of nickel-based superalloy GH4169

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ABSTRACT

The aim of this paper was to identify the grain size effect on the small fatigue crack initiation and growth mechanisms of nickel-based superalloy GH4169. Results showed that there was a transition of fatigue crack initiation mechanism between fine-grained material and coarse-grained material. Small fatigue crack growth rates were almost constant across a wide range of crack lengths. Once the surface crack length reached the critical size of 200 μm, the crack would propagate fairly quickly. At a given experimental condition, the scattering of fatigue lives of the parallel specimens was dependent on the crack initiation mechanisms.

1. Introduction

The nickel-based superalloy, GH4169 has similar microstructure and mechanical properties to those of Inconel 718. This alloy is widely used in aviation, aerospace and nuclear industries due to its high performance/price ratio, good formability and weldability [1,2]. The components fabricated by nickel-based superalloy, such as aerospace turbine disks, often undergo fatigue loading, leading to their premature failure. Previous studies showed that the stages of crack initiation and small crack propagation accounted for more than 70–80% of the total fatigue life [3]. The critical crack length that leads to the fatigue failure of aero-engine disks may be less than a few millimeters [4]. Hence, in order to accurately predict the fatigue lives of components and establish the damage tolerance design methodology, it is important to identify the fatigue crack initiation and growth mechanisms of the material.

The microstructure, especially the grain size has important influence on the low cycle fatigue (LCF) resistance of nickel-based superalloys [1]. For Inconel 718 alloy, most of the previous studies were mainly focused on the effect of grain size on the LCF properties and crack initiation mechanism [1,4–6]. Two common conclusions could be drawn from the previous studies, namely two different fatigue crack initiation mechanisms were found for Inconel 718 alloy and the fatigue lives of parallel specimens at a given testing condition exhibited significant scattering. The shape and dimensions of the parallel specimens are the same and they are prepared with the same processing and tested under the same testing condition. For instance, Alexandre et al. [1] found that fatigue cracks were preferentially initiated at second phase particles when the grain size was between 5 and 10 μm. On the other hand, typically transgranular crack initiation along the intense slip bands was

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Nomenclature

a	surface crack length
c	maximum crack depth
σ_{max}	maximum applied stress
σ_{ys}	yield strength
N	number of cycles
N/N_f	cycle ratio
N_f	number of cycles to fracture failure
N_0	number of cycles at which the first crack initiates
Δa	crack extension
ΔN	cyclic interval
da/dN	crack growth rate
ΔK	nominal stress intensity factor range
K_{max}	maximum stress intensity factor
v	Poisson's ratio
E	Young's modulus
R	stress ratio
κ	empirical constant
ϕ_m	monotonic crack tip displacement
ϕ_c	cyclic crack tip displacement

Abbreviations

SENT	single edge notch tensile
OM	optical microscopy
SEM	scanning electron microscope
EDS	energy dispersive spectrometer

observed for the specimens with large grain size, i.e., 150 μm. Both the above two crack initiation mechanisms were found for the specimen with a grain size of 40 μm. They suggested that the strength of the material decreased and plastic strain within the grains increased with increasing the grain size. In such a case, fatigue cracks tended to initiate at the grain boundaries. Some similar results were also obtained by Huang et al. [4] for nickel-based superalloy GH4169. Späth et al. [5] used more than 2750 cylindrical specimens to investigate the effect of grain size on the LCF behavior of Inconel 718 alloy. Results showed that the fatigue life generally increased with decreasing the grain size. They also found that the fatigue crack initiation mechanism was dependent on the grain size, namely, crack initiated from grains for specimens with large grain sizes and crack initiated from carbide for specimens with relatively small grain sizes. The scattering of fatigue lives of specimens with grain sizes smaller than 10 μm was obvious. The scattering can be reduced through distinguishing the two fatigue crack initiation mechanisms. More recently, Abikchi et al. [6] investigated the fatigue life and initiation mechanisms of Inconel 718 with two grain sizes, namely 7 μm and 10 μm. In addition to the above mentioned two fatigue crack initiation mechanisms, they also found the internal crack initiation on particles which led to the formation of fish-eye crack for the material with grain size of 7 μm.

Although the scattering of LCF lives of the parallel nickel-based superalloy specimens was often observed, the reason for it was still not clear. One possible reason may be that the total fatigue life not only depended on the crack initiation mechanism, but also depended on the small crack growth behavior. However, experimental studies on small fatigue crack growth behavior of superalloys 718 and GH4169 were relatively few in the open literature [1,4,7], although the long fatigue crack propagation behavior has been widely reported. Connolley et al. used acetate replica method to record the process of fatigue crack initiation, growth and coalescence of Inconel 718 notched specimens at 600 °C [7]. They found that small crack growth rate was approximately constant across a wide range of crack lengths. However, the investigations regarding the grain size effect on the small fatigue crack growth of GH4169 alloy have not yet been found. The aim of this paper was to investigate the effect of grain size on the small fatigue crack initiation and growth mechanisms of GH4169 by using the two-part silicon based replica method [8]. The fatigue life scattering of parallel specimens which was related to the small fatigue crack growth behavior was also discussed.

2. Experimental procedures

2.1. Materials

The chemical composition of the material GH4169 used in this paper was in wt.%: 0.035 C; 0.08 Si; 0.03 Mn; 0.003 S; 0.006 P; 18.93 Cr; 3.02 Mo; 1.03 Ti; 5.11 Nb; 0.53 Al 0.003 B; 0.08 Co; 19.46 Fe; balance Ni. The specimens used for fatigue