

Modeling and Simulation of Microstructurally Small Crack Formation and Growth in Notched Nickel-base Superalloy Component

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Studies on microstructurally small fatigue cracks have illustrated that heterogeneous microstructural features such as inclusions, pores, grain size distribution as well as precipitate size distribution and volume fraction create stochasticity in their behavior under cyclic loads. Therefore, to enhance safe-life and damage-tolerance approaches, accurate modeling of the influence of these heterogeneous microstructural features on microstructurally small crack formation and growth from stress raisers is necessary. In this work, computational micromechanics was used to predict the high cycle fatigue of microstructurally small crack formation and growth in notched polycrystalline nickel-base superalloys and to quantify the variability in the driving force for formation and growth of microstructurally small crack from notch root in the matrix with non-metallic inclusions. The framework involves computational modeling to obtain three-dimensional perspectives of microstructural features influencing fatigue crack growth in notched nickel-base superalloys, which accounts for the effects of nonlocal notch root plasticity, loading, microstructural variability, and extrinsic defects on local cyclic plasticity at the microstructure-scale level. This approach can be used to explore sensitivity of minimum fatigue lifetime to microstructures. The simulation results obtained from this framework were calibrated to existing experimental results for polycrystalline nickel-base superalloys.

KEY WORDS: Microstructurally small crack; Crystal plasticity; Nickel-base superalloy; Fatigue life

1. Introduction

Current fatigue life prediction methods mainly consider two stages: crack initiation and crack propagation. Crack initiation is further decomposed into crack nucleation, microstructurally small crack (MSC) growth, and physically small crack (PSC) growth^[1,2]. Crack nucleation is the locally complex process of crack formation on the microstructural scale, which is characterized by smooth fracture surfaces at angles inclined to the loading direction^[3]. MSCs have a size on the order of microstructural features in a material, which ranges from micrometers to hundreds of micrometers^[4]. The length of PSCs is on the order of 5–10 times of the microstructural scale. Microstructurally and physically small cracks can be identified depending on the reasons for their lack of similitude and their dissimilarities with long cracks^[5]. Crack propagation is long crack growth to final

fracture. The length of long cracks is more than 10–20 times of the microstructural dimension. Long crack propagation to final failure is the stage of damage accumulation that is well characterized using the linear elastic fracture mechanics (LEFM) or the elastic–plastic fracture mechanics (EPFM). The total fatigue life can be determined by adding the loading cycles for crack nucleation, MSC growth, PSC growth, and crack propagation. However, fatigue life prediction tools are currently limited in their ability to incorporate MSC growth^[6] especially for materials with complex microstructure such as nickel-base superalloys.

Nickel-base superalloys are a high performance material subject to severe operating conditions. They are widely used in aero engine components and power-plants because of their high strength and good creep, fatigue, and corrosion resistance at high temperatures^[7,8]. Fatigue failure is of great importance for these components for the catastrophic consequence caused by cyclic stresses and strains. Fatigue failure of nickel-base superalloys is a limiting factor for their reliable use in many engineering applications. The total fatigue life of nickel-base superalloys is the addition of numbers of cycles for crack nucleation and growth through the MSC, PSC, and long crack growth regimes^[9]. Studies^[7–10] have shown that the crack nucleation and MSC growth of nickel-base superalloys is different from that in

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homogeneous base materials due to the high level of residual stresses, complex microstructure, complicated loading, and internal defects. Experimental studies on polycrystalline nickel-base superalloys indicate that the crack nucleation and MSC regimes are very important stages since the majority of the fatigue life in nickel-base superalloys used as turbine disc is spent in these fatigue regimes during service^[11]. Prior research studies on the fatigue behavior of nickel-base superalloys are focused on higher length-scale phenomena and on direct experimental observation of fatigue damage processes^[12]. Under high cycle fatigue (HCF) situation, crack nucleation and MSC growth is highly heterogeneous at the grain scale and the influence of microstructure on the small crack formation and growth has shown to be significant^[13]. Microstructure features such as inclusions, pores, grain size distribution, grain boundaries as well as precipitate size distribution and volume fraction often have main influences on determining the crack formation and growth in both low cycle fatigue (LCF) and HCF in nickel-base superalloys^[9]. Since polycrystalline nickel-base superalloys such as IN 100 is prepared by powder metallurgy technique, the presence of inclusions and pores in the microstructure always provide crack nucleation sites. Therefore, among these features, inclusions such as carbides within a grain or near grain boundaries and pores in the polycrystalline material can significantly reduce the number of cycles to form a fatigue crack because the incompatibility of deformations between the inclusions and the surrounding materials leads to local plasticity^[14].

Over the past several decades, many attempts have been made to determine the critical value of inclusion size, below which the effect of inclusions on fatigue life could be ignored, while above which, the influences of inclusions should be examined and taken into consideration carefully. Uhrus^[15] showed that for ball bearings, only oxide inclusions, which are more than 30 μm in diameter, should be taken into consideration for assessment of the fatigue life. Nishijima et al.^[16] studied standard Japanese tempered martensitic steels, which showed that the critical size of inclusions is around 45 μm . The inclusions with an irregular shape and sharp edges could lead to larger stress concentrations compared to inclusions with smooth shape and edge, which further make it easier for crack initiation. In real microstructure, inclusions have irregular shape^[17]. In this work, computational micromechanics was used to predict the high cycle fatigue of MSC formation and growth in notched polycrystalline nickel-base superalloys IN 100 and to quantify the variability in the driving force for MSC growth in the matrix with non-metallic inclusions. The simulation results were used to characterize the fatigue strength reduction effects of notched components with non-metallic inclusions at a given probability of failure. The approach presented in this study can also be used to support expensive and time consuming experiments as well as assist in the design of better fatigue resistant safety-critical notched components with defects such as non-metallic inclusions and pores.

2. Material System

The material used in this work was the polycrystalline IN 100 superalloy, which is commonly used for hot section applications in aircraft engines and power generation turbines due to its capability of retaining strength in excess of 1 GPa at high temperature. The yield strength of this nickel-base superalloy decreases with increase in temperature, with an anomalous behavior

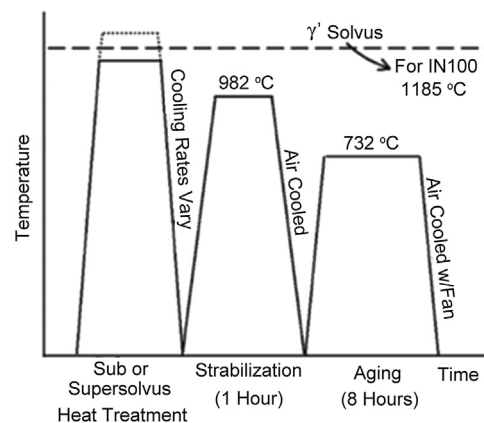


Fig. 1 Heat treatment process for IN 100^[18].

between 500 and 800 °C^[17]. Polycrystalline IN 100 was prepared using powder metallurgy technique. Powder process is able to produce the alloys with fine-grained microstructures with high strength and structure homogeneity due to its capability in reduction of individual phase segregation. In order to obtain the desired final microstructure, attention should be paid to heat treatment process, which determines the end product form and application. Optimum heat treatments should be designed for yielding the desired microstructure and phases. Typically, a heat treatment process for IN 100 has a three-step thermal cycle: solution treatment at high temperature, stabilization/stress relief at an intermediate temperature, and low temperature age as shown in Fig. 1^[18]. The first cycle stands for a subsolvus or supersolvus heat treatment with temperature at 1143 or 1205 °C for 2 h, the second cycle is stabilization process at 982 °C for 1 h and the last step is aging process at 732 °C for 8 h^[18].

After heat treatment, two major phases are apparent: disordered γ and ordered γ' as shown in Fig. 2^[19]. Three different size distributions of γ' precipitates can be founded in this image. These size distributions are the primary γ' precipitate, the secondary γ' and the tertiary γ' , respectively, which are distinct through the diameters. The largest γ' precipitates are the primary γ' with a diameter around 1 μm formed during the first step of heat treatment, whose size and distribution is set by the solution treatment temperature; the secondary precipitate with diameter around 0.1 μm is the product of cooling process from solution temperature and is modified by the stabilization temperature; and tertiary precipitates with diameter around 0.01 μm form during subsequent aging process, which are coherent with the γ matrix. Two types of carbides are seen in the microstructure of IN 100:

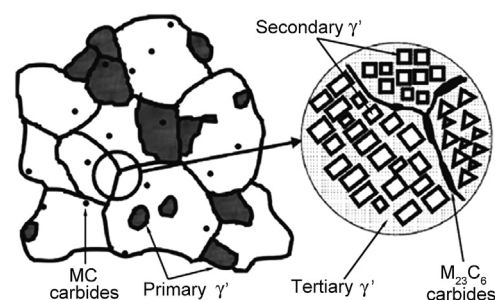


Fig. 2 Schematic diagram of the microstructure of IN 100 after heat treatment^[19].

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