Effect of inclusion defect on fatigue failure of FGH96 superalloy at 600 °C

Guolei Miao¹, Tong Sun¹,², Xiaodong Wang²,*

¹Chengdu Holy Industry & Commerce Corp. Ltd, Pengzhou, Sichuan 611936, China
²School of Aircraft Engineering, Nanchang Hangkong University, Nanchang, China;
*Corresponding author: Xiaodong Wang, E-mail: 1103672377@qq.com

Abstract: High cycle fatigue experiments were conducted at 600 °C to study the effect of manufacture defect on crack initiation behaviour of FGH96. The experiments were performed at different stress levels to considering the coupling effect of loading and defect. The stress ratio was selected at 0.05. The results revealed that the fatigue life behaviour are much different in different loading levels. In order to examine the crack initiation mechanism, Scanning electron microscopy (SEM) method was used to analyze the failure surfaces. Different failure modes including surface cracking, sub surface cracking as well as internal crack initiation were found. The tested fatigue lives were found to have a strong relation with the mode of the crack initiation.

1. Introduction

The second generation of damage tolerant PM Superalloy, FGH96, has been widely used in advanced aero-engine at home and abroad due to its excellent yield strength, fatigue and creep resistance[1]. Its actual working condition temperature has been raised to 750 °C. However, in the process of preparing superalloys by powder metallurgy, it is inevitable to bring in non-metallic inclusions (mainly ceramic inclusions). These inclusions and surface processing conditions have a great impact on the fatigue performance of turbine disk. Therefore, the fatigue property of PM Superalloy is very important[2].

Cashman [3-4] performed strain controlled low cycle fatigue experiments of Rene 95 and Rene 88DT powder metallurgy Ni-base superalloy at elevated temperature. At high stress levels, failures were mainly controlled by surface initiated mechanism, while at low stress levels, failures were controlled by internal initiated mechanism. IN100 is the first generation of P/M processed nickel-based superalloy. With the improvement of powder metallurgy processing, the number of nonmetallic inclusions and pores has been decreased. The competing fatigue failure modes may be different. The competing fatigue failure behavior may be effected by inclusion content, specimen volume, stress level, temperature and so on. The data of competing failure behavior of the second generation of P/M processed nickel-based superalloy are not sufficient, especially under LCF load.

The main target of the work presented in current paper is to understand the roles of microstructure in competing fatigue failure behaviors of FGH96, the second generation of polycrystalline powder metallurgy nickel-based superalloy of China. In addition to the supplementary data, the present research work was intended to investigate the effect of stress level on competing failure modes. Fatigue experiments in a large sample were performed at 600 °C at four different stresses ranging from 900MPa to 1200MPa (from high cycle fatigue to low cycle fatigue). Scanning Electron Microscope (SEM) analysis were conducted to investigate the roles of defects and characteristics of microstructures in competing modes.
2. Materials and Experimental procedures

2.1. Materials
The P/M superalloy (named FGH96) was tested in the current research. Before fatigue tests, the microstructure was examined by Electron backscatter diffraction (EBSD). The grain was characterized as shown in Figure 1. Meanwhile, there is no significant texture can be found. Therefore, the microstructure of the alloy is uniform.

![Inverse pole map and texture pole figure of FGH96 grains](image1)

Figure 1. Inverse pole map and texture pole figure of FGH96 grains

2.2. Experimental procedure
The fatigue test samples were cut from a turbine disk. The geometry dimensions of the tested samples is demonstrated in Figure 2. All of the fatigue tests were conducted in load control at stress ratio (R) of 0.05. The frequency was set at 5 Hz. The maximum stress was 900, 1000, 1100 and 1200 MPa, respectively. In order to avoid the manufacturing defect effect on the surface, all of the sample was electropolished using an electrolyte of 55% ethanol with 35% butyl cellusolve and 10% perchloric acid at 25 V and -20°C.

![The geometry dimensions of the tested samples](image2)

Figure 2. The geometry dimensions of the tested samples

3. Results and discussion

3.1. Fatigue life results
Figure 3 shows the probability of the fatigue lives under various stresses. The probability of the fatigue failure was described as a function of fatigue lives in the double logarithmic coordinate system. The results indicated that it seemed a double lognormal distribution was found under maximum stress of 1200 MPa. The short life stage and long life stage followed different trends. There may be some different damage mechanism controlling the failure process.
3.2 Fatigue Damage mechanisms

3.2.1 Surface vs. internal initiated failures. In order to explain the fatigue life behavior of FGH96, the fracture surfaces of tested samples were examined to address the fatigue crack initiation mechanism through SEM analysis. Figure 4 showed the SEM evidences of the typical failure modes. The results showed three types of fatigue initiation modes, which were surface crack initiation (see Figure 4 (a)), sub-surface crack initiation (see Figure 4 (b)) and internal crack initiation (see Figure 4 (c)). As it can be seen in Fig. 4 (b), the fatigue initiation site located at the subsurface. Therefore, partial crack would grow in the interior of the material. In Figure 4 (c), the crack initiated in the interior of the sample. The fatigue initiation site as well as fatigue crack growth located in the material interior. However, the fatigue tests revealed that the lives of the samples with internal crack initiation were longer than the other two. Cashman [4] reviewed that fatigue crack growth life for specimens tested in vacuum were longer than in air. The surrounding of internal crack initiation site seem to be a vacuum-like environment. Therefore, a longer fatigue lives can be achieved when the crack initiation located in interior of the alloy.

![Figure 3](image-url) Probability of the fatigue lives under various stresses.

Figure 3. Probability of the fatigue lives under various stresses.

3.2.2 Surface inclusion initiated vs. internal inclusion initiated modes. In order to investigate the roles of microstructures in the fatigue variability, all the fatigue fracture surfaces were analyzed. As shown in Figure 5, all the fatigue failures occurred with inclusions or cleavage. There were no pore-initiated failures.

![Figure 4](image-url) Three crack initiation modes found in the fracture surfaces

Figure 4. Three crack initiation modes found in the fracture surfaces
The probability of occurrence of surface inclusions initiated is gradually reduced with decreasing of stress level, simultaneously the probability of occurrence of sub-surface inclusions initiated failure failures are shown in Figure 6. The sizes of long axis of the equivalent ellipse of the inclusions are about 37 μm, 35 μm and 48 μm respectively, slightly larger than the average grain size.

Inclusions at surface were the controlling microstructure of the life-limiting at higher stress levels. If there were no inclusions at the surface, the fatigue life would be extended and the fatigue variability would be reduced at higher stress level. At lower stress levels (1000MPa, 900MPa), the crack initiation occurred with internal inclusions. Internal inclusions initiated fatigue lives did not make the fatigue life variability larger at lower stresses.

![Figure 5](image)

**Figure 5.** Surface inclusion initiated vs. internal inclusion initiated modes

3.2.3 Surface facet initiated vs. internal facet initiated failure modes. As shown in Figure 7, there were three kinds of crystallographic facet initiated failure modes: 1) surface facet initiated; 2) sub-surface facet initiated; 3) internal facet initiated. The probability of occurrence of internal facet initiation increases gradually with decreasing of stress level. Figure 8 is the typical characteristic of fracture surface of facet initiation failure. The initiation sites of facet-initiated fatigue failures contained a group of small crystallographic facets. With the decrease of stress level, the initiation location contains more facets. For the internal failure mode, “fish eye” fracture surfaces were observed. In the center of the “fish eye”, a bigger facet was surrounded by many small facets, as shown in Figure 8(c). The radius of equivalent circle of the center facet is slightly larger than the average grain size.

![Figure 6](image)

**Figure 6.** Surface inclusions initiation Surface inclusions initiations VS. sub-surface inclusions initiation: (a) Surface inclusions initiation, 1200MPa, Nf=9,504; (b) Sub-surface inclusions initiation, 1000MPa, Nf=217,527; (c) Internal inclusions initiation, 900MPa, Nf=1079,795
4. Conclusions
The fatigue of a P/M superalloy was conducted at 600°C. The main conclusions are summarized as the following points. Firstly, The results indicated that it seemed a double lognormal distribution was found under maximum stress of 1200 MPa. The short life stage and long life stage followed different trends. Secondly, three failure modes, which were surface, sub-surface and internal initiated cracking, were observed. The controlling mechanism of cracking initiation was a combination of microstructure and load level. Secondly, the experimental results show that the fatigue life of the specimens with the fatigue initiation point and the fatigue crack growth in the interior is longer than that of the other two specimens, which may be due to the greater influence of different crack initiation positions on the fatigue damage mechanism.

References
[1] Wenjing Zhou, Wuyang Wang, Progress and application of Powder Superalloy [J]. Journal of
aeronautical materials, 2006, 26(3): 244-250

[2] Xingling Liu, ChunHU Tao, Damage behavior and life prediction of FGH96 PM Superalloy [J]. Failure analysis and prevention, 2011, 6(2): 124-129

[3] Cashman G T. A review of competing modes fatigue behavior [J]. International Journal of Fatigue, 2010, 32(3): 492-496.

[4] Cashman G T. A statistical methodology for the preparation of a competing modes fatigue design curve [J]. Journal of Engineering Materials and Technology, 2007, 129(1): 159-168.

[5] Jha S. COLLABORATIVE RESEARCH AND DEVELOPMENT (CR&D) Delivery Order 0037: Mechanisms Causing Fatigue Variability in Turbine Engine Materials [R]. UNIVERSAL TECHNOLOGY CORP DAYTON OH, 2008.