Fatigue Crack Initiation and Propagation Mechanism of FGH96 PM Superalloy

Zhao Kai1,2,3,4*, He Yu-huai1,2,3,4
1 AECC Beijing Institute of Aeronautical Materials, Beijing 100095, China
2 Beijing Key Laboratory of Aeronautical Materials Testing and Evaluation, Beijing 100095, China
3 Key Laboratory of Science and Technology on Aeronautical Materials Testing and Evaluation, Aero engine corporation of China, Beijing 100095, China
4 Aviation Key Laboratory of Science and Technology on Materials Testing and Evaluation, Beijing 100095, China
*Corresponding author’s e-mail:372537284@qq.com

Abstract. FGH96 is regarded as a promising powder metallurgy superalloy for high-temperature / pressure turbine disc in aerospace industries due to its high resistance / defect tolerance and high working temperature up to 750 ℃. The initiation and propagation mechanism of FGH96 PM superalloy is researched by in-situ fatigue experiments. The result shows that the crack of gap samples initiates and propagates at the same stress level at 25 ℃ and 300 ℃. At 300 ℃, there are no creep characteristics such as the intergranular characteristics found in the sample fracture. The crack at 300 ℃ has a faster initiation and propagation process compared to the crack at 25 ℃, especially in the late stage of fatigue. The increase of the crack propagation rate of the sample is unrelated to the creep, mainly due to oxidation. Oxidation reduces the fatigue life of materials because it accelerates the initiation and propagation of transgranular cracks.

1. Introduction
In-situ fatigue test under scanning electron microscope (SEM) is a technique which the sample table in SEM is replaced in-suit fatigue assembly. The external loading is applied and the movement of the scanning electron beam is controlled by an external magnetic field to conform to the deformation of the sample[1-3]. The process of crack initiation and propagation can be intuitively understood by tracking and observing the in-situ tensile and fatigue processes of SEM, especially the changes of the sample surface during the loading process, which provides abundant information for the study of crack initiation and propagation[4-6].

In the first half of the 20th century, cyclic slip was considered to be the main cause of microcrack formation. In the 1930s, Gough suggested that fatigue cracks were formed because cyclic slippage exceeded the limit of local strain hardening[7-8]. 1939, Orowan adopted this viewpoint who believed that the exhausting of local ductile led to the increase of the local stress and crack eventually[9]. 1953, Head presented the first crack propagation rate model according to the concept. Forsyth found that materials smooth surfaces could form peaks and valleys due to different slip surfaces being invaded and extruded when materials suffered cyclic strain or stress and the slip band or stayed slip band was
Hunsche and Ma[11] found that the interface between stayed slip band and adjacent matrices had a large dislocation density gradient. It was easy to generate the microcrack with the discordance of strain.

2. Experimental
FGH96 P/M superalloy was used to machining samples (Figure 1). The alloy in this investigation was an advanced nickel-base PM superalloy. The chemical composition of P/M nickel-based superalloy was listed in table 1. In-situ fatigue test was performed in the SEM-SERVO 550 machine and the test conditions were listed in table 2.

![Figure 1. In-situ fatigue test sample](image)

Table 1. Main chemical composition of FGH96 P/M superalloy in wt%.

| Cr   | Co   | W    | Mo   | Nb   | Al  | Ti   | Zr   | Fe   |
|------|------|------|------|------|-----|------|------|------|
| 15.5~ | 12.5~ | 3.8~4.2 | 3.8~4.2 | 0.60~ | 1.95~ | 3.55~ | 0.03~ | ≤0.50 |
| 16.5 | 13.5 |      |      | 0.80 | 2.3  | 3.90 | 0.06  |       |
| Mn   | N    | O    | H    | C    | S   | P    | B    | Si   |
| ≤0.02 | ≤0.006 | ≤0.015 | ≤0.001 | 0.045~ | 0.060 | ≤0.0012 | ≤0.010 | 0.012~ | ≤0.10 |
|      |      |      |      |      |     |      |      |      |

Table 2. FGH96 PM superalloy in-situ fatigue test conditions.

| Sample style | Temperature | Gap depth/mm | Thickness/mm |
|--------------|-------------|--------------|--------------|
| Unilateral gap | 25°C | 0.5 | 0.40 |
| Unilateral gap | 300°C | 0.5 | 0.42 |

3. Results and discussion

3.1 In-situ fatigue test (25°C)
In-situ fatigue test process (25°C) was listed in table 3. At the beginning, the frequency and the stress were low. After that, the frequency was stable at 3Hz and the stress increased. The purpose of this process was to avoid the thin sample warping.

Table 3. In-situ fatigue test process (25°C).

| Stress/MPa | 500 | 600 | 700 | 750 | 800 | 850 | 850 | 850 | 850 | 850 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Fatigue cycles/Cycle | 306 | 1000 | 1240 | 2097 | 2003 | 1044 | 972 | 974 | 1122 | 1070 | 270 |
| Frequency/Hz | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
850MPa, the crack A appearance was shown in Figure 2c. It could be seen that the crack A expanded obviously and its length was 42.8μm. But some microcracks in the middle were not connected. The crack B was not expanded clearly. After 974 cycles of 850MPa, the crack A expanded obviously and its length was 84.1μm. Microcracks in the middle were connected. Also, the crack B was not expanded clearly (Figure 2d). After 1,122 cycles of 850MPa, the crack A expanded to 154μm, and cracks in the middle broadened. Also, the crack B was not expanded clearly (Figure 2e). After 1,070 cycles of 850MPa, the crack A expanded to 320.8μm (Figure 2f). After 270 cycles of 850MPa, the sample broke. The total fatigue life of the sample was 12,098 cycles and the initiation life was 6646 cycles, so the initiation life accounted for 55% of the total life.

During the initiation and propagation of the whole fatigue crack, the crack slipped under the action of the cyclic load and the stress concentration. The microcrack appeared at the edge of the gap and expanded through the grain. When the crack encountered the grain boundary, deflection would occur. At the stress concentration in front of the main crack, new microcracks may form and connect with the main crack to expand. The main crack expanded with the increase of cycle, however, the microcrack next to it did not develop obviously.
The sample fracture was observed in the SEM. The fracture characteristic of the fatigue propagation in the first stage was class cleavage (Figure 3a). The length of the crack was 65μm and the life in the first stage was 2,503 cycles, so the crack propagation rate in the first stage was 2.5×10⁻⁵mm/cycle. The fracture characteristic of the fatigue propagation in the second stage was fatigue stripe (Figure 3b). The length of the crack was 266μm and the life in the first stage was 2,949 cycles, so the crack propagation rate in the second stage was 9×10⁻⁵mm/cycle. The fracture characteristic of the fatigue propagation in the late stage was dimple (Figure 3c).

![Figure 3. The sample fracture characteristic](image)

3.2 In-situ fatigue test (300°C)

In-situ fatigue test process (300°C) was listed in Table 4. The grain appearance near the gap of the sample before loading was shown in Figure 4a. When the temperature increased to 300°C without load, the material properties were unchanged. When the stress increased to 500MPa, there was no crack appeared. When the stress increased to 850MPa and the sample was operated under the stress for 1174 cycles, 50.67μm long crack appeared (Figure 4b). After 300 cycles of 850MPa, the crack propagated to 87.84μm (Figure 4c). After 302 cycles of 850MPa, the crack propagated to 176.9μm (Figure 4d). After 290 cycles of 850MPa, the sample broke. The microcrack appeared at the edge of the gap and expanded through the grain. When the crack encountered the grain boundary, deflection would occur.

The sample fracture was observed in the SEM. The length of the fatigue propagation in the first stage was short. There was little fracture characteristic so that it was too hard to distinguish the first stage and the second stage. The fatigue stripe could be observed near the source region (Figure 5a). The total length of the first stage and the second stage was 337μm and the total life was 2066 cycles, so the crack propagation rate of the total stages was 1.63×10⁻⁴mm/cycle (Figure 5b).

| Stress/MPa | Fatigue cycles/Cycle | Frequency/Hz |
|------------|----------------------|--------------|
| 500        | 504                  | 1            |
| 600        | 498                  | 3            |
| 700        | 1062                 | 3            |
| 750        | 1040                 | 3            |
| 800        | 1278                 | 3            |
| 850        | 1174                 | 3            |
| 850        | 300                  | 3            |
| 850        | 302                  | 3            |
| 850        | 290                  | 3            |

(a) The grain appearance near the gap (b) 50.67μm long crack
4. Discussion
The in-situ fatigue test process at 300°C was as same as the test at 25°C. The total fatigue life of the sample at 300°C was 6448 cycles. The crack appeared when the stress increased to 850MPa. The sample broke after 2,066 cycles of 850MPa. The crack at 300°C had a faster initiation and propagation process compared to the crack at 25°C. The total fatigue life of the sample at 25°C was 12,098 cycles. Also, the crack appeared when the stress increased to 850MPa. The sample broke after 5,452 cycles of 850MPa.

At 300°C, the crack expanded so fast in the last 290 cycles that the length of the crack could not be confirmed. However, the length of the fatigue zone was 337μm measured by the SEM and the total life was 6,448 cycles, so the nominal crack propagation rate was 0.052μm/cycle, which included the fatigue first stage and the fatigue second stage. At 25°C, the length of the fatigue zone was 320.8μm and the total life was 12,098 cycles, so the nominal crack propagation rate was 0.027μm/cycle.

The temperature of 300°C caused the crack to initiate and expand rapidly, especially in the late stage of fatigue. The behavior that the fatigue life of materials decreased with the increased of temperature was usually caused by time-related damage. Generally, there were two kinds of time-related damage at high temperature, namely, creep and oxidation[12]. At 300°C, there were no creep characteristics such as the intergranular characteristics found in the sample fracture. Therefore, the increase of the crack propagation rate of the sample was unrelated to the creep, mainly due to oxidation. Oxidation reduced the fatigue life of materials because it accelerated the initiation and propagation of transgranular cracks.

5. Conclusions
1) At 25°C and 300°C, the crack of gap samples initiates and propagates at the same stress level;
2) At 300°C, there are no creep characteristics such as the intergranular characteristics found in the sample fracture;
3) The crack at 300°C has a faster initiation and propagation process compared to the crack at 25°C, especially in the late stage of fatigue;
4) The increase of the crack propagation rate of the sample is unrelated to the creep, mainly due to oxidation. Oxidation reduces the fatigue life of materials because it accelerates the initiation and propagation of transgranular cracks.

Acknowledgments
Authors wishing to acknowledge assistance or encouragement from colleagues, special work by technical staff or financial support from the National Science and Technology Major Project (2017-IV-0004-0041).

References
[1] Jablonski D A. (1981) The effect of ceramic inclusions on the low circle fatigue life of low carbon Astroloy subjected to hot isostatic pressing. Mater Sci Eng, 48: 189.
[2] Bretheau T, et al. (1988) Inclusion/matrix mechanical interaction an in situ study by tensile and fatigue tests in the scanning electron microscope. Strength of Metals and Alloys. Finland. pp. 87-91.
[3] Xie Xishan, Zhang Lina, Zhang Maicang et al. (2002) Micro-mechanical Behavior Study of Non-metallic Inclusions in Nickel-base P/M Superalloy. Acta Metallurgica Sinica, 6: 635-642.
[4] Ambroise W H, et al. (1987) Crack initiation from the interface of superficial inclusions. Conference: Mechanical Behavior of Materials - V, Beijing, pp. 169-174.
[5] Mander J M, Kortovich C S. (1981) Development of Materials and Process Technology for Dual Alloy Disks. NASA-CR-165224.
[6] Harf F H. (1985) Properties and Microstructurals for Dual Alloy Combinations of Three Superalloys with Alloy 901. NASA-TM-86987.
[7] Schijve J. (2003) Fatigue of structures and materials in the 20th century and the state of the art. International Journal of Fatigue, 25(8): 679-702.
[8] Barter S, Molent L, Goldsmith N, et al. (2005) An experimental evaluation of fatigue crack growth. Engineering Failure Analysis, 12(1): 99-128.
[9] Hunsche A, Neumann P. (1986) Quantitative measurement of persistent slip band profiles and crack initiation. Acta Metallurgica, 34(2): 207-217.
[10] Zou Jinwen, Wang Wuxiang. (1999) Characteristic and quality control of inclusions in P/M superalloy. Powder Metallurgy Technology, 7: 201-206.
[11] Guo Wei-min, Feng di, Wu Jian-tao. (2002) Research and development of P/M superalloy metallurgic techniques. Journal of Materials Engineering, 3: 44-48.
[12] Ma BT, Laird C. (1989) Overview of fatigue behavior in copper single crystals-I. Surface morphology and stage I crack initiation sites for tests at constant strain amplitude. Acta Metallurgica, 37(2): 325-336.