Fatigue behavior and mechanism of FV520B-I in ultrahigh cycle regime

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Abstract

FV520B-I which is a kind of martensitic precipitated hardening stainless steels is usually applied to manufacture centrifugal compressor impellers. The centrifugal compressor impellers may fail from ultrahigh cycle fatigue induced by wake flow. Aim to assess ultrahigh fatigue life of impellers, fatigue tests up to $10^9$ cycles were carried out by ultrasonic fatigue testing machine to research ultrahigh cycle fatigue (UHCF) behavior and mechanism of FV520B-I. The results show that the $S-N$ curve of FV520B-I can be divided into two segments at $10^7$ cycles apparently. The fatigue cracks almost all initiated from the surface of an impeller when the fatigue life less than $10^7$ cycles and then from the subsurface inclusion of an impeller when the fatigue life more than $10^7$ cycles. In other words, the fatigue behavior of FV520B-I is in accordance with UHCF except one specimen’s crack occurred at surface surprisingly when fatigue cycles greater than $10^7$. Through the fracture morphology to be observed and measured, the reasons of “fish eye” area and GBF area formation were discussed, and the relationship of fatigue strength, fatigue life, and characteristic area size were researched by relative models.

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Keywords: FV520B-I; Ultrahigh cycle fatigue; S-N curve; Fatigue strength; Fatigue life

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1. Introduction

The centrifugal compressor is the core equipment of gas deliveries used in energy, petroleum, chemical, and other important industries. As impellers are the key components of a centrifugal compressor, high cycle fatigue and ultrahigh cycle fatigue induced by wake flow of the impellers are the main failure modes. The research of ultrahigh cycle fatigue behavior and mechanism of the centrifugal compressor impeller materials can make us have a profound understanding of the impeller fatigue design and remanufacturing, and it is beneficial to guaranteeing the safety of centrifugal compressor long life operation.

Fatigue includes three types of low cycle fatigue, high cycle fatigue, and ultrahigh cycle fatigue according to failure cycles. Cracks usually initiate from the surface of the impellers in low cycle fatigue and high cycle fatigue, and from the subsurface of the impellers in high cycle fatigue and ultrahigh cycle fatigue, especially for the latter. The "fish eye" morphology is a typical feature of ultrahigh cycle fatigue fracture[Nakajima, et al. (2006); Sakai, et al.(2002); Ochi, et al.(2002)]. Ultrahigh cycle fatigue mechanism is different from the mechanism of low cycle fatigue and high cycle fatigue."Hydrogen embrittlement"[Murakami, et al. (1999)] and “dispersive decohesion of spherical carbide”[Shiozawa, et al. (2006)] are two main theories in ultrahigh cycle fatigue regime at now. Due to hydrogen surrounding the inclusion have been observed[Otsuka, et al.(2005); Murakami, et al. (2006)], it is widely believed that hydrogen play an important role in ultrahigh cycle fatigue. The ultrasonic fatigue testing as having very high loading frequency(20kHz) has become an important method of ultrahigh cycle fatigue researches, although there are some disadvantages needing to overcome such as frequency effect and specimen temperature rising.

FV520B-I is an important material to manufacture centrifugal compressor impellers for its good corrosion resistance, high strength, high hardness, and well weldability. The authors of this paper tested the ultrahigh fatigue property of FV520B-I up to $10^9$ cycles by ultrasonic fatigue testing machine, and analyzed the ultrahigh cycle fatigue behavior and mechanism of the steel through observing fatigue fracture morphology and measuring characteristic area size.

2. Experimental material and experimental method

2.1. Experimental material

FV520B-I is a martensitic precipitation hardening stainless steel, and its main chemical compositions and mechanical properties are shown in Table 1 and Table 2.

| Table1.Chemical compositions of FV520B-I. |
|------------------------------------------|
| C | Si | Mn | P | S | Ni | Cr | Cu | Nb | Mo | Fe |
|---|----|----|---|---|----|----|----|----|----|----|
| ≤0.07 | ≤0.07 | ≤1.0 | ≤0.03 | ≤0.03 | 5.0-6.0 | 13.2-14.5 | 1.3-1.8 | 0.25-0.45 | 1.3-1.8 | Bal. |

| Table2.Mechanical properties of FV520B-I. |
|------------------------------------------|
| Tensile strength $R_m$/MPa | Yield strength $R_p$/MPa | Vickers hardness $H_v$/kgf · mm$^2$ |
| 1170 | 1029 | 380 |

2.2. Experimental method

The fatigue tests were conducted on a Shimadzu USF-2000 at a resonance frequency of 20 kHz and room temperature in air ambient with a resonance interval of 500 ms per 500 ms (i.e. the machine stops for 500 ms when it operates for 500ms), and stress ratio $R$=-1. Compressive cold air was used to cool the specimen during ultrasonic fatigue testing to prevent excessive temperature rising. The specimens were machined into the shape and dimension as shown in Fig.1. Specimens were polished by 2000 mesh emery paper before fatigue testing.
3. Experimental results

3.1. Microstructure

The cross-section microstructure observations of specimens are shown in Fig.2. It can be seen that the lath martensite with fine organization structure, ferrite with uniform distribution, and some small inclusions distributed in the microstructure.

3.2. S-N curve

The S-N curve obtained from all the specimens are shown in Fig.3. According to fracture observations, there are two crack initiation modes: surface initiation and subsurface initiation. It can be seen that the fatigue strength decreases with increasing number of cycles, and there is no "traditional fatigue limit" in the vicinity of $10^7$ cycles.
cycles. The slope of the S-N curve before demarcation area is relatively gentle and the slope of the S-N curve after demarcation area become slightly steep. Crack initiating of FV520B-I from surface matrix, subsurface matrix and subsurface inclusion are three modes of fatigue crack initiation in the demarcation area. It is surprising that fatigue crack could initiation from surface matrix when fatigue life close to $10^8$ cycles in ultrahigh cycle fatigue regime. This means there is a competition between surface initiation and subsurface initiation not only in demarcation area but also in ultrahigh cycle fatigue regime.

3.3. Fracture surface observation

The fracture surfaces of the specimens which fatigue life higher than $10^7$ cycles were observed by SEM. Fatigue cracks initiated from internal inclusions in almost all specimens, and fatigue cracks initiated from surface substrate in one specimen. Further investigations show the situation of inclusions in the fatigue sources. Generally there was a single inclusion in a fatigue source, and clusters in fatigue sources were rare as shown in Fig.4. All inclusions are Al$_2$O$_3$ through energy spectrum analysis.

![Fracture surface observation](image)

**Fig. 4.** Initiations of fatigue cracks (a) initiating from surface substrate($\sigma=575\text{MPa}, N_f=7.99\times10^7$); (b) initiating from single inclusion($\sigma=650\text{MPa}, N_f=1.44\times10^7$); (c) initiating from clusters($\sigma=650\text{MPa}, N_f=1.94\times10^7$)

When a crack initiated from subsurface, the "fish eye" boundaries were obvious in fatigue fracture; but the "fish eye" boundaries were fuzzy in another fatigue fracture as shown in Fig.5. The authors believed that a closely connection between the existence of the "fish eye" area and the distance of the crack source to the specimen surface. When a crack source is close to the specimen surface, the subsurface crack transforms into surface crack quickly, so the stress intensity factor has a significant increase and the rate of the fatigue crack growth has a significant increase too. The wide difference of the crack growth rate in two sorts resulting in the formation of "fish eye" area; when a crack source is away from the specimen surface, the stress intensity factor and crack growth rate increase area gradual process, thus the fuzzy of a "fish eye" boundaries formed, even it can be considered that the "fish eye" area does not exist.

![Fracture surface observation](image)

**Fig.5.** Fracture morphology (a)$\sigma=600\text{MPa}, N_f=1.32\times10^8$; (b)$\sigma=600\text{MPa}, N_f=6.45\times10^7$
There is a highlight area around the inclusion (granular bright facet, GBF), as shown in Fig. 6(a), and this area is relatively rough and different from the flat region of usual fatigue sources. There are different views about the reason of the formation GBF area, but scholars generally agree that hydrogen is the cause of the formation of the GBF area. When a crack initiates from the subsurface substrate, the GBF area is not exist, as shown in Fig. 6(b). The concentration of hydrogen around the internal inclusion is usually much higher than that in the subsurface substrate, and therefore it may also be verified that hydrogen plays an important role in the GBF zone formation from another side.

![Fig. 6. Fatigue source area (a) \(\sigma = 600\text{MPa}, N_f = 6.45 \times 10^7\); (b) \(\sigma = 700\text{MPa}, N_f = 3.38 \times 10^6\)](image)

4. Discussion

4.1. FV520B-I fatigue strength prediction

Murakami, et al. dealt with some small flaws or inclusions as a crack by linear elastic fracture mechanics, and the area was defined as defects projected area perpendicular to the direction of maximum principal stress. When the crack growth around inclusions was considered as a critical condition, they established "inclusion equivalent projected area model" including the hardness, the size of inclusions, and the fatigue strength [Murakami et al.(1983); Murakami et al.(1994)]. As its physical quantity is less and can be measured easily, this model is widely used. The fatigue strength of high strength steel which contains nonmetallic inclusions inside can be expressed as:

\[
\sigma_w = \frac{1.56 \times (HV + 120)}{(\sqrt{\text{area}_m})^{1/6}}
\]

(1)

And \(HV\), the Vickers hardness of the matrix, kgf/mm\(^2\); \(\sqrt{\text{area}_m}\) the square root of the inclusion projection area perpendicular to the maximum principal stress axis in the plane, approximately equal to the diameter of the inclusions, in unit of \(\mu\)m.

Taking the maximum inclusion size, 16.4\(\mu\)m, into the Eq. (1), the fatigue strength can be obtained, that is, \(\sigma_w = 490\text{MPa}\). The fatigue strength of FV520B-I at 10\(^{9}\)cycles extrapolated by the S-N curve trend is about 550MPa. There is a large deviation between results predicted by the model and by the experiment. The model mentioned above is established on basis of the relevant specific experimental results and the assumption of existing fatigue limit, so it can be understood that the fatigue life predicted by the model is significantly lower than that by experiments.
4.2. FV520B-I fatigue life prediction

Generally, the theories related with the establishment of the models to predict ultrahigh cycle fatigue life may be corrected by modifying several parameters such as the inclusion size, stress amplitude, and so on. The model of Paris law which is the most widely used fatigue life prediction model in low cycle fatigue is also used in ultrahigh cycle fatigue regime. This model was based on two assumptions: (1) the fatigue life consumed all in GBF area formation; and (2) the fatigue crack growth follows the Paris law. Usually, the GBF area size is great larger than the inclusion size, then Eqs. (2)~(4) are the basic relationships to predict fatigue life.

\[
\Delta K = 0.5\sigma \sqrt{\pi \text{area}_{in}} \\
d\frac{da}{dN} = C(\Delta K)^m \\
\Delta K^n \cdot N_f / \text{area}_{in} = \frac{2}{(m-2)C}
\]

And \(\Delta K\) the stress strength factor; \(\sigma\) stress; \(d/dN\) crack growth velocity; \(N_f\) fatigue life; \(\sqrt{\text{area}_{in}}\) the square root of the inclusion projection area perpendicular to the maximum principal stress axis in the plane, approximately equal to the diameter of the inclusions; \(C, m\) constant. Through linear fitting \(N_f\) and \(\sqrt{\text{area}_{in}}\) of specimens, we get \(m = 2.348, C = 3.33 \times 10^{-7}\) according to slope and intercept of the fitted straight line easily. Substituting the values of \(C, m, \Delta K_{in}\) and \(\sqrt{\text{area}_{in}}\) into Eq. (4), the fatigue life prediction is compared with experimental results, as shown in Table 3.

| Stress amplitude \(\sigma\) (MPa) | The square root of inclusion projection area \(\sqrt{\text{area}_{in}}\) (\(\mu m\)) | Fatigue life obtained by experiments \(N_f\) | Fatigue life predicted by Eq.(4) \(N_f\) | Deviation \(\frac{\%}{N_f}\) |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|------------------|
| 675                            | 12.5                            | 2.37E+07                        | 3.72E+07                        | 56.90%           |
| 650                            | 10                              | 1.44E+07                        | 4.22E+07                        | 193.32%          |
| 650                            | 16.4(clusters)                  | 1.94E+07                        | 3.88E+07                        | 99.77%           |
| 650                            | 4.4                             | 2.72E+07                        | 4.87E+07                        | 79.13%           |
| 625                            | 10.8                            | 2.01E+07                        | 4.57E+07                        | 127.35%          |
| 625                            | 13.8                            | 2.27E+07                        | 4.38E+07                        | 92.90%           |
| 625                            | 13.3                            | 4.16E+07                        | 4.41E+07                        | 5.94%            |
| 600                            | 10.9                            | 5.45E+07                        | 5.02E+07                        | -7.87%           |
| 600                            | 11.9                            | 6.45E+07                        | 4.95E+07                        | -23.33%          |
| 575                            | 15.6                            | 2.45E+08                        | 5.21E+07                        | -78.72%          |
| 550                            | 13.2                            | 6.83E+08                        | 5.96E+07                        | -91.28%          |

According to the comparison between the fatigue lives predicted by the model and obtained by experiments, the model prediction is significantly higher than the experimental results in high-stress areas; while the model prediction is much lower than the experimental results in low-stress areas. This may be due to the underlying assumptions of model is discrepancy with ultrahigh cycle fatigue essence.
5. Conclusions

The $S_N$ curve of FV520B-I shows not only that the material does not exist "the traditional fatigue limit", but also that the curve possesses two apparent segments which is divided significantly by the crack initiation modes transiting from surface initiation to subsurface initiation. Crack initiating at surface matrix and subsurface inclusion are the two modes of FV520B-I fatigue crack initiation in UHCF. There is a closely connection between the existence of the "fish eye" area with the distance of subsurface crack source from specimen surface. The closer the subsurface crack source to specimen surface is, the more obvious the “fish eye” boundaries are. When the crack initiated from the subsurface substrate, the GBF area is not exist, which may be verified that hydrogen play an important role in GBF zone formation. There are larger deviations between the model predicting results and experimental results of FV520B-I fatigue strength and fatigue life. This reveals that to continually develop the prediction models is necessary based on clear physical mechanism in ultrahigh cycle fatigue regime.

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