The VHCF experimental investigation of FV520B-I with surface roughness Ry

J L Wang, Y L Zhang, M C Ding, Q C Zhao

School of Mechanical Engineering, Dalian University of Technology, Dalian, China

E-mail: zylgzh@dlut.edu.cn

Abstract: Different surface roughness type (Ra and Ry) has different effect on the VHCF failure and life. Ra is widely employed as the quantitative expression of the surface roughness, but there are few fatigue failure mechanism analysis and experimental study under surface roughness Ry. The VHCF experiment is conducted out using the specimen with different surface roughness values. The surface roughness Ry is employed as the major research object to investigate the relationship and distribution tendency between the Ry, fatigue life and the distance between internal inclusion and surface, and a new VHCF failure character is proposed.

1. Introduction

FV520B-I has been widely applied in the manufacturing of all different kinds of large-scale mechanical equipment [1-2] and the core mechanical parts for its numerous good mechanical properties. Its fatigue life generally required to reach or over $10^7$ cycles, which implies that the main factor causing the very-high cycle fatigue failure is the internal inclusion. However, the poor working condition always results in the deterioration of the surface quality during the working process. It has been adopted that the bad surface quality (that is big surface roughness value) will weaken the fatigue property to resist fatigue failure especially the fatigue strength of the material, especially the deep groove of the surface will affect the VHCF fatigue life. Different surface roughness type (Ra and Ry) has different effect on the VHCF failure and life, such as: the surface roughness can change the stress distribution of the specimen to affect internal failure sites that is the internal inclusion location.

Quite a few theories have been proposed based on the investigation of fatigue failure caused by surface roughness. Stenberg [3] investigates the influence of the surface quality to the fatigue strength. Different codes and design recommendations are provided to improve the fatigue strength of high strength steel S700 and S960. Lacerda [4] studied the effectiveness of the evolution of surface roughness to the fatigue strength under different loads and fatigue life, and the relationship between these parameters can be determined according to this study. Li [5] focuses on the fatigue life estimation with different surface roughness, S-N curves and P-S-N curves are presented in this study, and crack initiation life and crack propagation life are estimated based on the classic fatigue life model. Silva and Bagehorn [6] study the influence of surface roughness on the fatigue property of titanium alloy, it was found that the small differences of surface roughness will result in the big reduction of the fatigue strength. And the effectiveness of each treatment to the fatigue property is analyzed in detail. Zhang [4] carried out a investigation about the influence of surface roughness to VHCF life, the relationship between surface roughness and fatigue life is proposed.

Generally, Ra is widely employed as the quantitative expression of the surface roughness. But Ra means the average value of the surface quality, so it is too conservative to the quantitative analysis of
VHCF failure. Instead of Ra, Ry means the deepest groove of the surface roughness will be suitable for the quantitative analysis of VHCF failure to investigate the coupling effect of surface roughness and internal fatigue defect to VHCF life. Moreover, the Ra can be the same or in the same level for different specimens, while the value of Ry must be different. So Ry can be employed to analysis the qualitative and quantitative relationship between the surface roughness and fatigue life.

In this paper, a more detailed and targeted research is carried, the main research focuses on the study of the very-high cycle fatigue failure mechanism affected by surface roughness Ry, and the proposition of the new VHCF failure rule. Further study of effectiveness of Ry to VHCF life is carried out. A new qualitative relationship between the D_{a-s} (the distance between the internal inclusion and the surface) and the Ry is proposed based on the fatigue failure analysis, also the new qualitative relationship between D_{a-s} and fatigue life will be proposed to reflect the effectiveness of Ry to the VHCF life.

2. The very-high cycle fatigue experiment

The material studied in this research is martensitic precipitation hardening stainless steel FV520B-I. The surface roughness of the specimen is set according to the application of FV520B-I in the actual working condition and Ra is employed as the processing standard which are divided into four levels with the comprehensive consideration of actual working condition, the processing condition and the test requirement: Ra_{1} ≤ 0.1μm, 0.1μm < Ra_{2} ≤ 0.2μm, 0.2μm < Ra_{3} ≤ 0.3μm, 0.5μm ≤ Ra_{4} ≤ 0.8μm. The Ry can be obtained according based on the specimen manufacturing process. D_{a-s} can be measured according to the SEM observations.

Standard hourglass type test specimen is employed as the specimen in this experiment, and the details of the geometrical shape and size are designed according to the elasticity modulus and density as shown in Fig.1.

USF-2000 ultrasonic fatigue test system is employed in this experiment with an operating frequency of 20 kHz. The mean stress is set to zero which presented that the stress ratio r = -1. The room temperature (20°C) was used, which are close to the actually situation in application. The intermittent ratio is set to 1:2 (working 250ms and stop 500ms), at same time, air cooling is employed to avoid the influence of heat. Both stress amplitude and the relevant fatigue life will be recorded.

3. The effectiveness of surface roughness Ry to VHCF life

(a) the relationship between the D_{a-s} and Ry; (b) the relationship between the D_{a-s} and N_{f}

3.1 The effectiveness of surface roughness Ry to the location of the internal inclusion
Fig.2.(a) shows that the overall distribution character: $D_{a-s}$ increases with the increase of the Ry under low stress amplitude situation and decreases with the increase of the Ry under high stress amplitude. A linear relationship is proposed to describe the relationship between the distance $D_{a-s}$ and Ry. With the stress amplitude increases from 500MPa to 600MPa, the slope decreases from positive value to negative.

When the stress amplitude is less than 575MPa and the fatigue life is in VHCF regime, with the increase of Ry, the surface stress concentration is more serious and the VHCF failure becomes more possible to originate from the surface. With the comprehensive competition between surface roughness and internal inclusion, it will take more time to get surface hardening and transit the fatigue crack from surface into internal site, so the relevant VHCF failure takes more time to initiate from the internal inclusion. With the stress amplitude increases, the extra effectiveness of stress amplitude to the VHCF failure leads to the decreases of the relevant VHCF life, but the fatigue life still in the VHCF regime, so the slope of the linear relationship just decrease with the increase of stress amplitude but is still positive value. When the stress amplitude increasing to 600MPa, the relevant life decreases close to high-cycle fatigue regime, and the discretion of the internal inclusion on VHCF failure decreases and the effectiveness of Ry to fatigue failure becomes more obvious. So the fatigue failure will prefer the site close to the surface, and with the influence of big stress amplitude, the fatigue failure occurs before the fatigue crack transfer into deeper location.

According to the above phenomenon, it can be further inferred that with the stress amplitude continuous increasing over 600MPa or the fatigue life is less than $10^{7}$ cycles, the effectiveness of surface roughness to the fatigue failure is more obvious than internal inclusion, so the fatigue initiation location moves closer to the surface and the surface failure will be obtained.

3.2 The effectiveness of distance $D_{a-s}$ to VHCF life

The Fig.2.(b) shows the distribution of distance $D_{a-s}$ and VHCF life. Under the stress amplitude condition, with the change of the location of the internal inclusion, the fatigue stress distribution will also change which results in the change of the VHCF life. So the VHCF life is not only affected by the internal inclusion size, but also the location of the internal inclusion.

The analysis in chapter 3.1 indicates that the big Ry will results in the long distance $D_{a-s}$ in the VHCF regime. Even the bad surface quality will weaken the fatigue property to resist fatigue failure especially the fatigue strength of the material, the internal inclusion is still the most serious factor to the fatigue life in the VHCF regime. So the effect of location of the internal inclusion is more obvious than the effect of the surface roughness to the VHCF life, and with the increase of the surface roughness Ry, both the distance $D_{a-s}$ and the relevant VHCF life increase. This conclusion is proposed under two preconditions: first, the same stress amplitude condition; second, in the VHCF regime.

Another situation is that when the stress amplitude is 600MPa, which is general bigger than the stress amplitude in VHCF regime. As the fatigue life is less than or close to $10^{7}$ cycles, the fatigue failure prefers the surface site and the influence of big stress amplitude is more obvious than the VHCF situation. A serious stress concentration will occur on the site with big surface roughness which will promote the fatigue crack initiation and propagation process and shorten the fatigue life. Moreover, with the internal inclusion gets closer to the surface, the fatigue failure will more prefer to the HCF failure which means the fatigue life decreases. So it is proposed that Ry increases, the distance $D_{a-s}$ decreases, and also the relevant HCF life decreases, and there is a positive correlation between the distance $D_{a-s}$ and both of the HCF life and VHCF life as shown in the Fig.2.(b).

A linear relationship is proposed to qualitatively describe the positive correlation between the distance $D_{a-s}$ and fatigue life $N_t$ in Fig.2.(b). With the decrease of the stress amplitude, the linear relationship moves along the X-axis to the right, and the slopes of the linear relationship in the Fig are almost constant under different stress amplitude conditions. This means the distance $D_{a-s}$ is affected by the coupling effect of surface roughness Ry and stress amplitude, and Ry is the dominant one.

In summary, it can be further inferred that there is a linear relationship between the Ry and VHCF life, and the more specific relationship is: in the VHCF regime, there is a positive correlation between
the Ry and VHCF life; in the HCF regime or fatigue life is close to $10^7$ cycles, there is a negative correlation between the Ry and fatigue life.

4. Conclusion

First, a linear relationship is proposed to describe the distribution relationship between $D_{as}$ and Ry: in VHCF regime, there is a positive relationship between the $D_{as}$ and surface roughness Ry; when the fatigue life is close to $10^7$ cycles or in HCF regime, there is a neglect relationship between the distance $D_{as}$ and surface roughness Ry.

Second, with the stress amplitude over 600MPa or the fatigue life is less than $10^7$ cycles, the effectiveness of surface roughness to the fatigue failure is more obvious than internal inclusion.

Third, the $D_{as}$ is employed as the intermediate variables to investigate the relationship between Ry and fatigue life and a linear relationship is proposed: in the VHCF regime, there is a positive correlation between the Ry and VHCF life; in the HCF regime or fatigue life is close to $10^7$ cycles, there is a negative correlation between the Ry and fatigue life.

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