# EFFECT OF MICROSTRUCTURE AND LOADING CONDITION ON VERY-HIGH-CYCLE FATIGUE LIFE OF HIGH-STRENGTH STEELS

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*Summary* A model is proposed for correlating the fatigue life, the stress ratio and the microscopic parameters (inclusion size and fine granular area size) at the fracture origin for high-strength steels with fish-eye mode failure in very-high-cycle fatigue regime. Then, the model is used to estimate the fatigue life. The results are in good agreement with the experimental data available in literature. The paper also indicates that the equivalent crack growth rate in the fine granular area accords with the form of the Frost and Dugdale law.

## INTRODUCTION

Differing from the low cycle and high cycle fatigue, the failure of high-strength steels in very-high-cycle fatigue (VHCF) regime is usually caused by the interior non-metallic inclusion and fish-eye mode failures often present with a fine granular area (FGA) observed in most cases around the inclusion at the fracture origin. Many investigations have shown that the loading condition along with the microstructure parameter (inclusion size and FGA size) plays an important role in the fatigue life, and more than 90% of fatigue life is spent on forming the FGA. So, it is essential to exploit the correlation of the microstructure parameter within fish-eye and the fatigue life of high-strength steels under different stress ratios in VHCF regime.

## MODEL AND RESULTS

Here, we consider a fish-eye mode failure with an FGA observed around the inclusion for high-strength steels in VHCF regime. It is assumed that the inclusion is seen as a mode-I internal penny-crack in an infinite solid, and that the maximum size of the plastic zone $r_{\mathrm{p}}$ involving the stress ratio $R$ for the penny-crack under plane strain is $r_{\mathrm{p}} = 2[\sigma(1-R)^m/\sigma_{\mathrm{Y}}]^2 d/(3\pi^2)$, where $d$ denotes the diameter of the internal penny-crack and $\sigma$ denotes the uniform remote tensile stress. The equivalent crack length is assumed to be related to the maximum size of the plastic zone, i.e.

$$a_i = a_{i-1} + \frac{2\beta_i}{3\pi^2}\left[\frac{\sigma_{\max}(1-R)^m}{\sigma_{\mathrm{Y}}}\right]^2 a_{i-1} \quad (i=1, 2, \ldots, N) \tag{1}$$

where $a_i$ denotes the equivalent crack length after the $i^{\mathrm{th}}$ cycles, $\beta_i$ is parameter, $a_0 = a_{\mathrm{In}} = 2\sqrt{area_{\mathrm{In}}}/\sqrt{\pi}$, and $area_{\mathrm{In}}$ denotes the inclusion projection area perpendicular to applied stress axis. Assuming that $\beta_i = \beta$, the fatigue life $N_f$ contributed by FGA is obtained by minimizing the integer $N$ that satisfies

$$a_{\mathrm{FGA}} \le \left[1 + \frac{2\beta\sigma_{\max}^2(1-R)^{2m}}{3\pi^2\sigma_{\mathrm{Y}}^2}\right]^N a_{\mathrm{In}} \tag{2}$$

where $a_{\mathrm{FGA}} = 2\sqrt{area_{\mathrm{FGA}}}/\sqrt{\pi}$, and $area_{\mathrm{FGA}}$ denotes the FGA area including the inside inclusion projection area. Consider that the fatigue life is very large in VHCF regime and most of the fatigue life is consumed to form FGA, thus Eq. (2) is solved approximately as

$$N_f = \frac{3\pi^2\sigma_{\mathrm{Y}}^2}{2\beta\sigma_{\max}^2(1-R)^{2m}}\ln\frac{a_{\mathrm{FGA}}}{a_{\mathrm{In}}} \tag{3}$$

From Eq. (3), it is seen that there are two parameters $\beta$ and $m$ involved. However, for $R=0$, it only has one parameter $\beta$. So one can first determine the parameter $\beta$ through fitting the experimental data for $R=0$. Here, the experimental data for a bearing steel (JIS SUJ2) in Refs. [2-4] are used, and the fatigue life $N_f$ consumed in FGA is taken as the total fatigue life in this paper. For determining the parameter $\beta$, Fig. 1 plots the experimental values of $\ln N_f - \ln\ln(a_{\mathrm{FGA}}/a_{\mathrm{In}})$ at $R=0$ available in Ref. [2] as a function of $\ln(\sigma_{\max}/\sigma_{\mathrm{b}})$ with the fitting results. It is observed that the values of $\ln N_f - \ln\ln(a_{\mathrm{FGA}}/a_{\mathrm{In}})$ and $\ln(\sigma_{\max}/\sigma_{\mathrm{b}})$ are well approximated by a linear relation, i.e. the fatigue life $N_f$ can be expressed as power function of $\sigma_{\max}/\sigma_{\mathrm{b}}$. For the determination of parameter $m$, another group of experimental data at $R=-1$ in Ref. [2] is used. By using the least square fitting, we obtain

$$N_f = \mathrm{e}^{11.617}(1-R)^{4.367}\left(\frac{\sigma_{\max}}{\sigma_{\mathrm{b}}}\right)^{-9.112}\ln\frac{a_{\mathrm{FGA}}}{a_{\mathrm{In}}} \tag{4}$$

Figure 2 plots the experimental fatigue life available in Refs. [2, 3] and the estimated one using Eq. (4) at different $R$.

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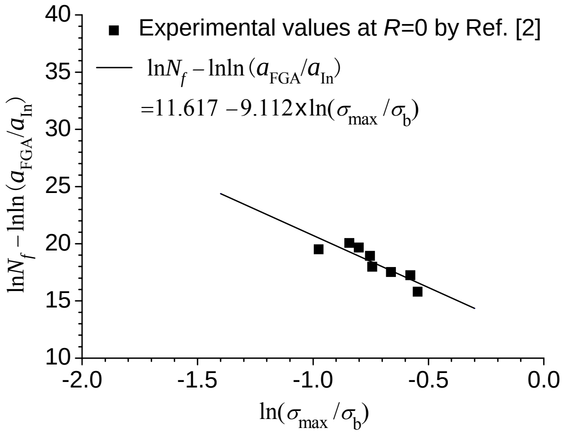


Fig. 1 Experimental values of $\ln N_f - \ln\ln(a_{\mathrm{FGA}}/a_{\mathrm{In}})$ as a function of $\ln(\sigma_{\max}/\sigma_{\mathrm{b}})$ with fitting results.

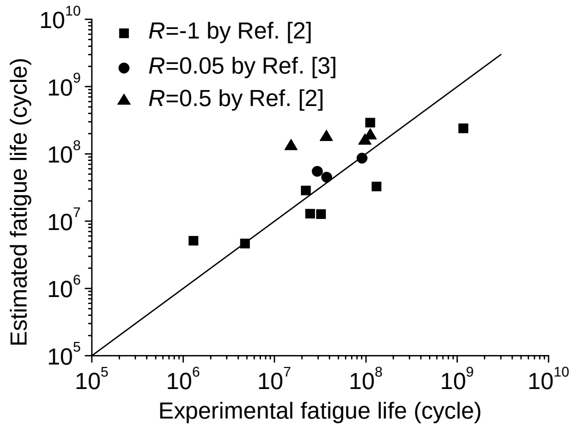


Fig. 2 Experimental fatigue life versus estimated one using Eq. (4) at different stress ratio $R$.

Figures 1 and 2 indicate that Eq. (4) correlates well the fatigue life, the stress ratio and the microscopic parameter at the fracture origin. Thus, the fatigue life of high-strength steels with fish-eye mode failure in VHCF regime is obtained as

$$N_f = \frac{1}{\alpha}\left[\frac{\sigma_{\max}(1-R)^{2m/l}}{\sigma_{\mathrm{b}}}\right]^{-l}\ln\frac{a_{\mathrm{FGA}}}{a_{\mathrm{In}}} \tag{5}$$

where the parameter $\alpha$, $m$ and $l$ can be determined by fitting the experimental data. From the above analysis, the equivalent crack growth rate is derived as $\mathrm{d}a/\mathrm{d}N = \alpha\sigma_{\mathrm{b}}^{-l}(1-R)^{2m}\sigma_{\max}^{l}a$. This indicates that the equivalent crack growth in FGA accords with the Frost and Dugdale law [1] for the given stress ratio $R$.

Figure 3 shows the estimated results of *S–N* curve using the present model with different inclusion sizes, which is compared with the corresponding experimental data available in literature. It is seen that the present model accords with the experimental data and reflects the effect of the inclusion size on the *S–N* curve. For the FGA size in Fig. 3, it is considered that $\Delta K_{\mathrm{FGA}}$ keeps constant [5] and is obtained by using $\Delta K_{\mathrm{FGA}} = 0.5\sigma_{\max}(1-R)\sqrt{\pi\sqrt{area_{\mathrm{FGA}}}}$ for $R>0$, and $\Delta K_{\mathrm{FGA}} = 0.5\sigma_{\max}\sqrt{\pi\sqrt{area_{\mathrm{FGA}}}}$ for $R \le 0$. The average value $4.535\mathrm{MPa}\cdot\mathrm{m}^{1/2}$ of $\Delta K_{\mathrm{FGA}}$ is used in Fig. 3.

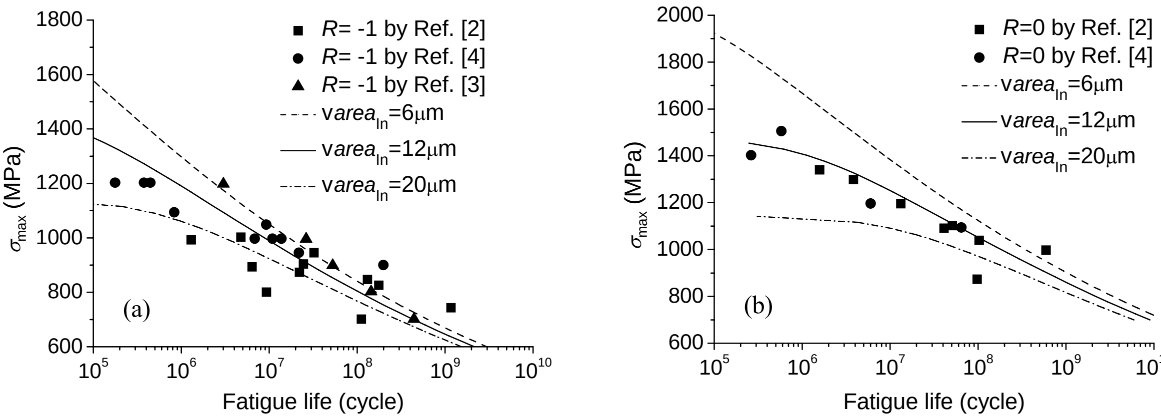


Fig. 3 Comparison of estimated *S–N* curve with experimental data in literature.

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**References**

[1] Frost N.E., Dugdale D.S.: The propagation of fatigue cracks in sheet specimens. *J. Mech. Phys. Solids* **6**:92-110, 1958.
[2] Shiozawa K., Hasegawa T., Kashiwagi Y., Lu L.: Very high cycle fatigue properties of bearing steel under axial loading condition. *Int. J. Fatigue* **31**:880-888, 2009.
[3] Nakajima M., Tokaji K., Itoga H., Shimizu T.: Effect of loading condition on very high cycle fatigue behavior in a high strength steel. *Int. J. Fatigue* **32**:475-480, 2010.
[4] Sakai T., Sato Y., Nagano Y., Takeda M., Oguma N.: Effect of stress ratio on long life fatigue behavior of high carbon chromium bearing steel under axial loading. *Int. J. Fatigue* **28**:1547-1554, 2006.
[5] Zhao A., Xie J., Sun C., Lei Z., Hong Y.: Prediction of threshold value for FGA formation. *Mater. Sci. Eng. A* **528**:6872-6877, 2011.