Describing and predicting the high temperature LCF life with the local equivalent strain energy approach

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1 INTRODUCTION

In connection with the high temperature low cycle fatigue (LCF) life problems at the edge of the leakage hole of aero-turbine disk, the LCF tests have been carried out at 300°C for cylindrical specimen with and without circumferential notch. A new parameter--local equivalent strin energy density (LESED) was suggested. It may be used to describe and predict the high temperature LCF life of notched specimens which are in the multiaxial state of stress and strin. Various mechanical parameters at the notch root of specimens were calculated by an elastic-plastic finite element program. Comparing the LCF life curves obtained with different methods, it is evident that the LESED approach can be used effectively not only for describing the LCF life curve of the notched specimens but also for predicting the LCF life of the notched specimens from the LCF life curve of the smooth specimens.

2 EXPERIMENT AND CALCULATION OF CONTROL PARAMETER

The configuration and dimension of the notched specimen is shown in Fig. 1. The material is iron-base superalloy GH36 used for aero-turbine disk. All fatigue tests were performed using MTS. The test was performed under strain range controlled condition. The strain rate was kept constant and in this test 2×10^{-4}/s, and triangular waveform was used. High-frequency induction heater was adopted to heat the specimen up to 300°C. The number of cycles to failure was defined as the number of cycles corresponding to the state of 5% decrease of the maximum load range.

Raising strain range step by step, the cyclic stress-strain curve at 300°C could be drawn. From which the constitutive equation may be obtained as:

$$(1) \qquad \varepsilon = \varepsilon^{e} + \varepsilon^{p} = \frac{\sigma}{E} + \left[\frac{1}{K}(\sigma - \sigma_s)\right]^{\frac{1}{n}}$$

where σ, ε ---stress and strain of the smooth specimen, E---Young's Modulus, K, n---material constant, σ_s---apparent yield stress. For GH36 at 300°C we have: $E=1.505\times10^{5}$ MPa, σ_s=454MPa, K=1122MPa, n=0.3586.

At present, several methods have been used to describe and predict the LCF life of notched specimen, such as the nominal stress method, the local strain method (Socie 1977) and J-integral method (Qingsheng 1982) etc., and Neuber's relationship (Neuber 1961) is usually used.

In this paper, we suggested a new control parameter, local equivalent strain energy density (LESED) $\overline{W}_{eff}$, which is effective also for multiaxial stress-strain state and power hardening material. The LESED approach assumed that the accumulation of equivalent strain energy is the major reason of LCF failure. And supposed that the life of notched bar and that of smooth bar are the same provided the LESED value of notched bar is equal to that of smooth bar.

The expression of LESED is

$$\overline{W}_{eff}=\overline{W}^{e}_{eff}+\overline{W}^{p}_{eff}=\int\bar{\sigma}\,d\bar{\varepsilon}^{e}+\int\bar{\sigma}\,d\bar{\varepsilon}^{p} \tag{2}$$

where $\overline{W}^{e}_{eff}$ and $\overline{W}^{p}_{eff}$ are elastic and plastic part of $\overline{W}_{eff}$ respectively. $\bar{\sigma}$, $\bar{\varepsilon}$ are equivalent stress and strain.

In the case of multiaxial stress state, from eq. (1) and eq.(2) we obtain

$$\overline{W}_{eff}=\overline{W}^{e}_{eff}+\overline{W}^{p}_{eff}=\frac{\bar{\sigma}^{2}}{2E}+\left[\frac{1}{K}(\bar{\sigma}-\sigma_{s})\right]^{1/n}\left(\sigma_{s}+\frac{\bar{\sigma}-\sigma_{s}}{n+1}\right) \tag{3}$$

Refering to Manson-Coffin formula, we can similarly write

$$\Delta\overline{W}_{eff}=\Delta\overline{W}^{e}_{eff}+\Delta\overline{W}^{p}_{eff}=A_{1}(N_{f})^{B_{1}}+A_{2}(N_{f})^{B_{2}} \tag{4}$$

in which, $\overline{W}_{eff}$ is used in the case of LCF and defined as

$$\Delta\overline{W}_{eff}=\int(\Delta\bar{\sigma}/2)\,d(\Delta\bar{\varepsilon}/2) \tag{5}$$

where A_1, A_2, B_1, B_2 are material constants.

An elastic-plastic finite element program was used to calculation the notch field parameter, such as stresses, strains, LESED and J-integral. The distribution of stresses and strains are given in Fig.2 and Fig. 3.

From the results summarized in Table 1, it is found that the traditional Neuber's relationship is unsatisfactory for multiaxial stress state especially under high stress/strain level.

Table 1.

ΔS(MPa)	K_σ	K_ε	K_t^*	results
635.6	1.027	0.279	1.360	$K_\sigma K_\varepsilon < K_t^2$
820.6	0.863	0.281	1.360	$K_\sigma K_\varepsilon < K_t^2$

*(савин, тульчии, 1976)

3 DESCRIBING AND PREDICTING LCF LIFE

According to the LCF test results for notched and smooth specimens at 300°C, the LCF life curves were obtained and shown in Fig. 4~6.

From LESED approach:

$$\Delta\overline{W}^{e}_{eff}=3.9288(N_{i})^{-0.1704} \qquad R=0.9926 \tag{6}$$

$$\Delta\overline{W}^{p}_{eff}=1077.0(N_{i})^{-0.9187} \qquad R=0.9984$$

From local strain method:

$$\left.\begin{aligned}\Delta\bar{\varepsilon}^{e}&=0.0072(N_{i})^{-0.084} && R=0.9883\\ \Delta\bar{\varepsilon}^{p}&=0.9850(N_{i})^{-0.825} && R=0.9964\end{aligned}\right\}\text{ by FE calculation} \tag{7}$$

(8) $\Delta\varepsilon^{e}=0.0155(N_i)^{-0.169}$ R=0.9840

$\Delta\varepsilon^{p}=26.450(N_i)^{-1.077}$ R=0.9850

$\Big\}$ by Neuber's relationship

From J-integral method:

(9) $\Delta J=612.4(N_i)^{-0.570}$ R=0.9888

Since it is necessary to take the LCF life curve of smooth specimens to predict the LCF life of notched specimens, the test data of smooth specimens are also shown in Fig. 4~5. The number of cycles to failure for smooth and notched specimens are listed in Table 2. Different control parameter gives different life, and the ratios N_i/N_f are not the same, too. From Fig. 4~5 and Table 2, it is obvious that LESED ($\overline{W}_{eff}$) is a better parameter for describing LCF life curve of GH36 at 300°C. The ratios obtained using LESED approach are less than 2.0. Comparing with other two methods, the prediction agrees with the experimental results better for the notched specimen in this case.

Table 2.

No.			15	16	17	18	19	20
Smooth specimen		N_f (cyc.)	430	452	570	562	970	1220
Notched specimen	$\Delta\overline{W}_{eff}$	N_i (cyc.)	766	878	915	1079	1176	2345
		N_i/N_f	1.78	1.94	1.61	1.92	1.24	1.92
	$\Delta\bar{\varepsilon}^{p}$	N_i (cyc.)	818	935	967	1125	1439	2510
		N_i/N_f	1.90	2.07	1.70	2.00	1.51	2.06
	$\Delta\varepsilon^{p}$	N_i (cyc.)	3565	3942	4029	4347	5600	8397
		N_i/N_f	8.29	8.76	7.07	7.07	5.10	6.88

4 CONCLUSION AND DISCUSSIONS

1. The LESED approach is successful for describing and predicting the life of notched specimens for GH36 at 300°C. It is guessed that this approach may be better for the material with higher strain hardening capacity.
2. It is found that Neuber's relationship is unsatisfactory for multiaxial stress state and especially under high stress/strain level.
3. It appears that J-integral is also an effecitve parameter for describing the LCF life, but rather difficult for predicting the LCF life of notched specimens.

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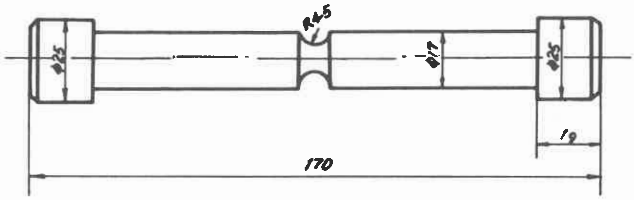

Fig.1 Notched specimen

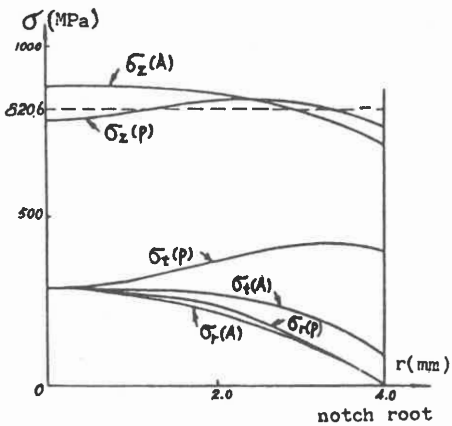

Fig.2 Distribution of stresses

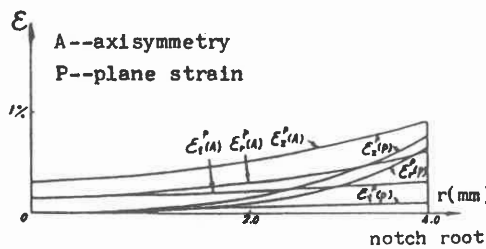

Fig.3 Distribution of strains

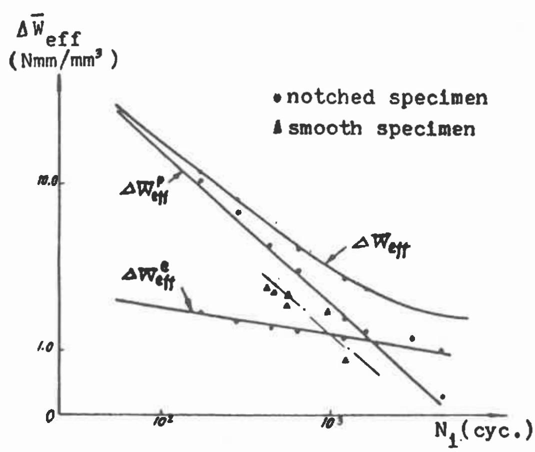

Fig.4 $\Delta\overline{W}_{eff}$ — N_i curve

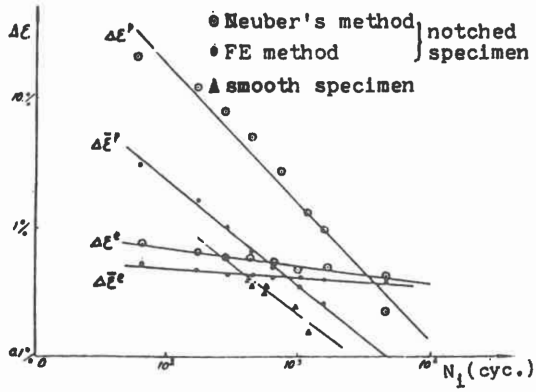

Fig.5 $\Delta\bar{\varepsilon}^{p}$, $\Delta\varepsilon^{p}$ — N_i curves

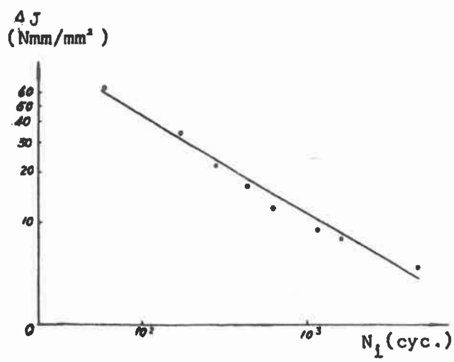

Fig.6 ΔJ — N_i curve