LOW CYCLE FATIGUE WITH HOLD-PERIODS AT HIGH TEMPERATURE FOR AN IRON-BASE SUPERALLOY GH36

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INTRODUCTION

Some componoents of aircraft engine subjected not only to low cycle stress or strain, but also to hold-periods at the maximum tensile stress or strain at high temperature. The fatigue life is reduced from that obtained during continuous-cyclic tests by the insertion of a hold period. Results from experiments indicate that fatigue life decreases as the hold period is increased. Many life-prediction methods have been formulated with varying degrees of success but their wide use is still questionable.

The main objective of the present investigation is to study the stress-strain behavior with hold periods at the maximum tensile strain at 650°C for an iron-base superalloy GH36. Relation between fatigue life and plastic strain range under such condition stated above was proposed. This relation may be used for predicting fatigue life. The microstructure and fracture surfaces of the alloy at different hold periods and different strain cycles were also examined.

EXPERIMENT

The test was carried out in air using axial symmetrical push-pull low cycle fatigue testing machine model ESH-50E at 650°C. The specimen was subjected to defferent hold time ranges (0,10,30 and 150 s) at the maximum tensile strain over strain ranges 0.832, 1.083, 1.5 and 1.98%. The strain rate was kept constant, taken to be 6×10^{-4}/s. The stress-strain response was measured using round specimens with a 10 mm gage length and 5 mm diameter. The strain-time waveform is shown in Fig. 1.

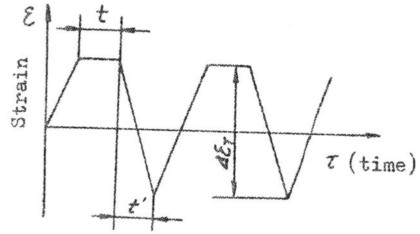

Fig. 1 Strain-time waveform (Schematic diagram)

The stress-strain hysteresis loops were recorded during the test, such as that shown in Fig. 2. The number of cycles to failure were determined by two methods: One is to determine the number of cycles corresponding to the point L at which the load range decreases by 10% on the maximum tensile load-cycle period, shown in Fig. 3. The other is to determine the number of cycles when an inflection point in the compression end of the hysteresis loop was first detectable. The results obtained by these two methods were nearly the same.

Thin foil transmission electron microscope observation was performed with a JEM-1000. The fatigue fracture surface analysis was conducted with a scanning electron microscope model JCXA-733.

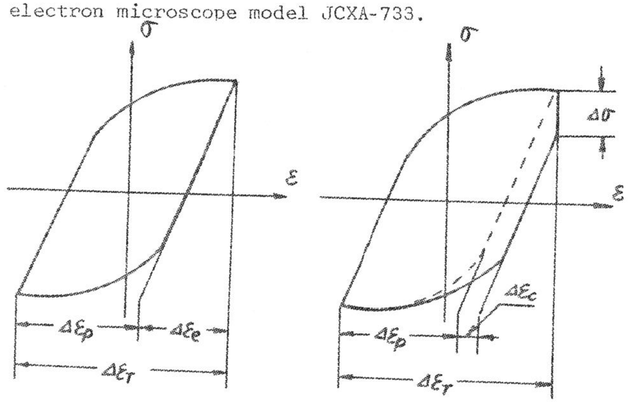

Fig. 2 Hysteresis loop obtained by strain control method shown in Fig. 1

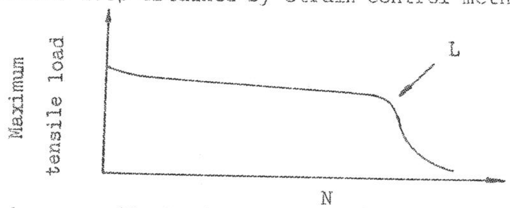

Fig. 3 Maximum tensile load versus number of cycles response

RESULTS AND ANALYSIS

It is well known that Manson-Coffin relation is

$$\Delta\varepsilon_p = \alpha N_f^{\beta} \tag{1}$$

Both the constants α and β in eqn. (1) are considered to be the function of the hold time at high temperature when creep of metal occurs, i.e $\alpha(t)$ and $\beta(t)$. The plastic strain range $\Delta\varepsilon_p$ in eqn. (1) has to be changed to $\Delta\varepsilon_{pc}$

$$\Delta\varepsilon_{pc} = \Delta\varepsilon_p + \Delta\varepsilon_c \tag{2}$$

Therefore, eqn. (1) should be expressed as

$$\Delta\varepsilon_{pc} = \alpha(t)\, N_f^{\beta(t)} \tag{3}$$

Experimental results showed the relation between $\Delta\varepsilon_{pc}$ and N_f at different hold time in Fig. 4. The plotted data in Fig. 4 have been found to be in good agreement with a straight line for a given hold time, i.e.

$$\Delta\varepsilon_{pc} = \alpha(t_i)\, N_f^{\beta(t_i)} \tag{4}$$

where t_i is the hold time. If we cónsider t = 1 s as zero hold time, from Fig. 5, the following relations were found to hold.

$$\alpha(t) = mt^n \tag{5}$$

$$\beta(t) = ht^k \tag{6}$$

where m, n, h and k are constants measured and listed in Table 1.

By combining Eqs. (3), (5) and (6), we got

$$\Delta\varepsilon_{pc} = mt^n N_f^{ht^k} \tag{7}$$

The plotted data in Fig. 5 are the results of the present study and other alloys [1,2,3], i.e. 316 stainless steel at the temperature ranges 625°C, 650°C and 750°C; Alloy SCM3 at 550°C; and 304 stainless steel at 593°C.

Fig. 5 showed that all the plotted data obtained from four kinds of alloys at five temperatures were in good agreement with eqs. (5) and (6).

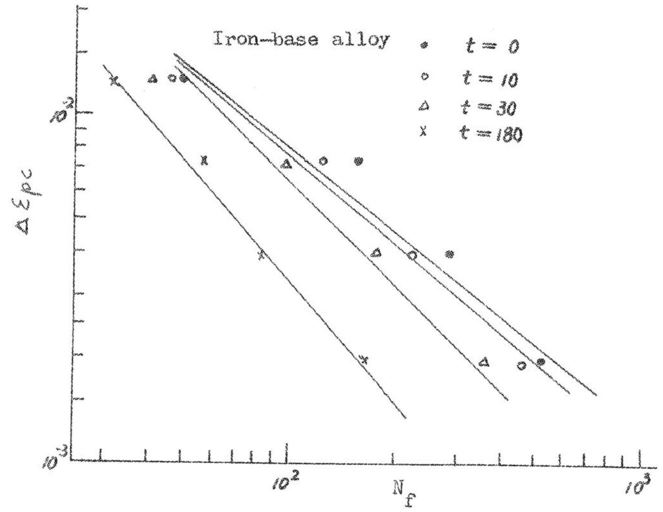

Fig. 4 Relation between inelastic strain range $\Delta\varepsilon_{pc}$ and number of cycles to failure N_f at 650°C

From Table 1, it was found that n/k=2, then the eqn . (7) becomes

$$\Delta\varepsilon_{pc} = mt^n N_f^{ht^{0.5n}} \tag{8}$$

When the hold time is too small, i.e. t approaches 1 s. as a limit, creep may be neglected, then $\Delta\varepsilon_{pc}$ becomes $\Delta\varepsilon_p$, and eqn.(8) becomes

$$\Delta\varepsilon_p = mN_f^h \tag{9}$$

eqn. (9) has the form like eqn. (1).

When the hold time is very long, i.e. t approaches infinity, fatigue may be neglected, while $N_f \to 1$ and $\Delta\varepsilon_{pc} \to \Delta\varepsilon_c$, then the eqn. (8) becomes

$$\Delta\varepsilon_c = mt^n \tag{10}$$

eqn. (10) is a creep equation.

When $t \gg t'$, $\nu = 1/t$, then eqn. (8) can be written as

$$\Delta\varepsilon_{pc} = m\nu^{-n} N_f^{h\nu^{-0.5n}} \quad (11)$$

Frequency (ν) is also implicitly taken into account in eqs. (7) and (8). So eqn. (7) may be used for predicting fatigue life under the condition that a hold period at the maximum tensile strain of plastic reversed-fatigue cycle is introduced.

From Fig. 2, we have

$$\Delta\varepsilon_c = \Delta\sigma/E \quad (12)$$

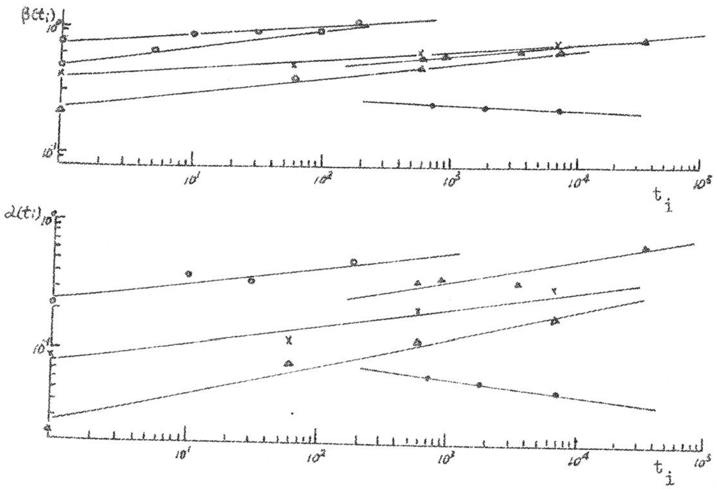

Fig. 5 $\alpha(t)$ and $\beta(t)$ versus hold time t

○ Iron-base alloy GH36 at 650°C ▵ 316 stainless steel at 650°C
× 316 stainless stell at 750°C ▫ Alloy SCM3 at 550°C
○ 316 stainless steel at 625°C ▲ 304 stainless steel at 590°C

where $\Delta\sigma$ is the relaxation stress during the hold time stage, as shown in Fig. 2. From eqn. (12), $\Delta\varepsilon_c$ can be obtained. The relation between $\Delta\varepsilon_c$ and the hold time t is shown in Fig. 6. it is clear that $\Delta\varepsilon_c$ is increased as the hold time increases. Then, from eqn. (2) $\Delta\varepsilon_{pc}$ is also increased. eqn. (8) shows that the fatigue life depends mainly upon the $\Delta\varepsilon_{pc}$, The fatigue life is decreased because of the increase of $\Delta\varepsilon_{pc}$. Therefore, the main reason for the decrease of the fatigue life is the increase of creep strain.

Table 1 Values of $\alpha(t_i)$, $\beta(t_i)$, m,n,k, and n/k

	t (sec)	$\alpha(t_i)$	m	n	$\beta(t_i)$	-h	k	n/k
Iron-Base Alloy (650°C)	0	0.2483	0.2541	0.1219	0.7466	0.7295	0.0668	1.8249
	10	0.3804			0.8449			
	30	0.3376			0.8657			
	180	0.4938			1.001			
AISI 316 (650°C)	0	0.0259	0.0284	0.2198	0.2232	0.2274	0.1182	1.85956
	60	0.0808			0.3879			
	600	0.1203			0.4701			
	7200	0.1796			0.6484			
AISI 316 (750°C)	0	0.0891	0.0797	0.1466	0.4155	0.3964	0.069	2.1246
	60	0.1168			0.4793			
	600	0.2072			0.6233			
	7200	0.3159			0.7580			
SCM3 (550°C)	0				0.4795	0.4865	0.1358	
	5				0.6189			
	95				0.8957			
AISI 304 (593°C)	600	0.3512	0.0985	0.1818	0.5876	0.3257	0.0893	2.0358
	900	0.3688			0.5962			
	3600	0.3356			0.6569			
	36000	0.7115			0.8419			
AISI 316 (625°C)	720	0.0668	0.1501	-0.1236	0.2940	0.4337	-0.0583	2.120
	1800	0.0591			0.2825			
	7200	0.0502			0.2575			

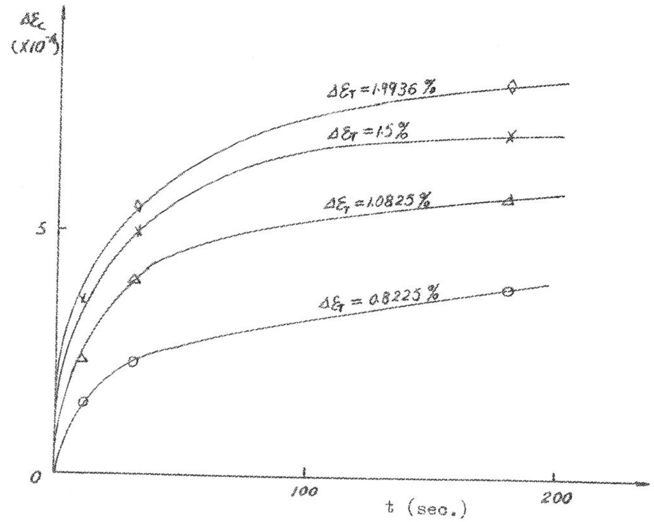

Fig. 6 Relation between $\Delta\varepsilon_c$ and the hold time t

Table 2 Effect of Hold Time on Fracture Characteristics

	Short hold time	Long hold time
Fracture surface features	Less rough comparatively	More rough comparatively
Fatigue striations	Transgranular and continuous striations spread over a large area	Intergranular striations separated by tearing ridges, and intensive local extension, etc.
Intergranular crack sites	Far away from the surface	Near the surface
Crack propagation	Linking-up of microvoids along grain boundaries	Linking-up of microvoids along grain boundaries

Microscopic observation indicated that microvoids were easy to form along grain boundaries when the hold time was long and cracks were easy to propagate along grain boundaries due to the linking up of microvoids. But the microvoids were difficult to form when the hold time is short.

Results from fracture surface analysis were summarized in Table 2. It is clear that the fracture morphology is closely correlated with the grain boundary creep-type cavitation and the growth of microvoids. As $\alpha(t)$ and $\beta(t)$ are function of hold time t, therefore, $\Delta\varepsilon_c$, $\alpha(t)$ and $\beta(t)$ are the physical quantities related to the formation and growth of microvoids along the grain boundaries.

CONCLUSION

1. Relation between plastic strain $\Delta\varepsilon_{pc}$ and fatigue life N_f with the introduction of a hold period at the maximum tensile strain for an iron-base superalloy GH36 at 650°C can be expressed as

$$\Delta\varepsilon_{pc} = \alpha(t)\ N_f^{\beta(t)} = mt^n N_f^{h(t)^{0.5n}}$$

2. $\alpha(t)$, $\beta(t)$ and $\Delta\varepsilon_c$ are the physical quantities related to the formation and growth of microvoids along grain boundaries.

3. The reason for the decrease of fatigue life due to hold time is the increase of creep strain which is attributed to the formation and growth of microvoids.

REFERENCES

[1] T.Y Udoguch et al, A Frequency Interpretation of Hold-Time Experiments on High Temperature Low-Cycle Fatigue of Steel for LMFBR, International Conference on Creep and Fatigue in Elevated Temperature Applications, C211 (1974).

[2] D.S. Wood et al, Some Creep/Fatigue Properties of Type 316 Steel at 625°C, Fatigue of Engineering Materials and Structures, Vol. 3, (1980) p.39-57.

[3] P.S. Maiya, Creep-Fatigue Life Prediction for Different Heats of Type 304 Stainless Steel By Linear-Damage Rate Approach, ANL-78-59.