Grain Size Effect in Low Cycle Fatigue of Steel Under Mean Strain

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ABSTRACT

Low cycle fatigue tests and small crack propagation tests were conducted on two kinds of annealed low carbon steel having fine and coarse grained microstructures with a special interest in the influence of grain refinement and mean strain on the low cycle fatigue life and on the fracture mode transition. Results show that (i) a surface to internal fracture mode transition occurs easily with an increase in mean strain and grain size and, (ii) the fatigue life of specimen failed in the surface fracture mode at a small plastic strain is not primarily controlled by the exhaustion of ductility. In such a regime, the characteristics of fatigue life under mean strain can be predicted by the calculation of a low cycle fatigue life on the basis of the law of small crack growth.

KEYWORDS

Fatigue; Low Cycle Fatigue; Fracture Mode Transition; Grain Refinement; Mean Strain; Small Crack Growth; Ductility

INTRODUCTION

It has been reported by the authors (Shimada et al., 1987, Kunio et al., 1988) that (i) in the low cycle fatigue of annealed low carbon steel including a very short life range less than N_f =100 cycles, there are three different types of fracture processes depending on the level of plastic strain range $\Delta \varepsilon_p$ which are shown schematically in Fig.1 (Shimada et al., 1987), (ii) a surface (Fig.1,Type A) to internal (Fig.1,Type C) fracture mode transition is encouraged by the tensile mean strain (Kunio et al., 1988) and (iii) in such a situation, a fatigue life is determined by the competition between two failure limit lines which correspond to the surface and internal fracture modes respectively (Fig.2) (Shimada et al., 1987).

However, many problems remain unsolved concerning the relation among the fracture mode transition, microstructure and magnitude of cyclic strain. The aims of the present study are (1) to make clear the relation between the fracture mode transition and the grain size of a microstructure, (2) to study the influence of grain refinement and of mean strain on the low cycle fatigue behavior.

MATERIALS AND TEST PROCEDURES

The material used in this investigation is low carbon steel having a carbon content of 0.20%. Two types of ferrite-pearlite microstructure with a ferrite grain diameter of about 65μm(Material-L) and 14μm(Material-S) were prepared for the purpose of making clear the influence of grain refinement on the low cycle fatigue behavior. The microstructures of both materials are shown in Fig.3. The heat treatment processes are presented in Table 1. The specimen configuration is shown in Fig.4. The mechanical properties of the materials are given in Table 2 together with the metallurgical parameters. Strain controlled low cycle fatigue tests were conducted using the servo controlled testing machine by detecting the change in the minimum diameter of the test specimen under mean strain ε_m = 0, 0.35 and 0.55 for a coarse grained steel and ε_m = 0 and 0.35 for a fine grained steel. Direct observation of a microfracture behavior was performed on the longitudinal section of the specimen after a given number of strain cycles. After polishing the surface with an alumina powder having a particle size of 0.3μm, hemispherical micropits were introduced at two positions on the minimum diameter surface of the specimen by means of electrodischarge machining. Observations of crack propagation behavior starting from surface micropits were performed. Measurements of crack length were taken using a replica method.

RESULTS AND DISCUSSION

Grain Size Effect in Fracture Mode Transition and Fatigue Life

First, the grain size effect in the fracture mode transition under mean strain will be described. The observation of a longitudinal section of the partially fatigued specimen showed that in the coarse grained steel an internal fracture mode occurs at $\Delta\varepsilon_p$>0.2, $\Delta\varepsilon_p$ >0.1 and $\Delta\varepsilon_p$>0.02 under mean strain ε_m= 0, 0.35 and 0.55 respectively. In contrast, in fine grained steel, no fracture mode transition was confirmed over the whole plastic strain range $\Delta\varepsilon_p$ from 0.003 to 0.4 under mean strain ε_m = 0 and 0.35. Some examples of those observations are shown in Fig.5. Consequently, it was proved that the fracture mode transition occurs more easily in the coarse grained steel than in the fine grained one.

Next, the effect of such a fracture mode transition on the fatigue life under mean strain will be discussed. The fatigue life curves for both materials are presented in Fig.6, where the narrow horizontal bands marked with the slashed lines in Fig.6(a) show the lowest level of $\Delta\varepsilon_p$ giving the internal fracture mode in the coarse grained steel. It should be noted that in the fine grained steel in which no fracture mode transition occur (See Fig.5(c)), fatigue lives can be expressed by a single Manson-Coffin curve (Coffin et al., 1954) over the whole range of $\Delta\varepsilon_p$ irrespective of the level of ε_m (0, 0.35). However, in a coarse grained steel, there exist a group of two failure limit lines (See Fig.2 for illustrating the two failure limit lines) which correspond to the surface and internal fracture mode respectively at each level of ε_m= 0, 0.35 and 0.55. In addition, the reduction of fatigue life associated with the internal fracture mode in the short life range (Fig.6(a)) can be observed at a smaller $\Delta\varepsilon_p$ as ε_m becomes larger. These behaviors are closely related to the evidences (Kunio et al., 1988) that the cracking of pearlite becomes easy inside the material with increase in a mean strain and that such a large amount of pearlite cracking has an effect of accelerating the internal crack growth.

Effect of Mean Strain on Fatigue Life for Surface Fracture Mode

In an earlier paper (Komotori and Shimizu, 1988), it was clarified that at a high level of $\Delta\varepsilon_p$ and ε_m giving an internal fracture mode, a fatigue life is controlled by the exhaustion of ductility under strain cycling and that a mean strain effect in such an extremely low cycle fatigue can be expressed by the following equation, which was originally proposed (Sachs et al., 1960), provided that α is 0.5 and C is equal to a fracture ductility ε_f.

$$\Delta\varepsilon_p N_f^{\alpha} = C - \varepsilon_m \quad (1)$$

In this chapter, however, attention will be focused on the effect of mean strain on the fatigue lives of the specimen failed in the surface fracture mode. Fig.7 gives the results of low cycle fatigue tests in such a regime, where the solid lines are the regression lines for the date of fatigue lives at ε_m = 0 and the dotted lines have been drawn by the Eq.(1). It is evident that while in a fine grained steel the fatigue lives under mean strain are in good agreement with the prediction by equation (1) (Fig.7(b)), Eq.(1) does not give a right prediction for the fatigue lives of coarse grained steel(Fig.7(a)). Thus, another approach would be required for the interpretation of the mean strain effect in the low cycle fatigue in a surface fracture mode. Recently, Harada has reported that the low cycle fatigue life can be predicted by the law of small crack growth under the condition of mean stress loading (Harada. To be published). Following the method (Harada et al., 1988), the calculation of a low cycle fatigue life under mean strain ε_m = 0.35 were performed on the basis of the law of small crack growth. The detailed procedure of such a calculation of fatigue life has been described in a previous paper (Komotori and Shimizu, 1987). The results are given by the following equations.

$$\text{Material L} \qquad \Delta\varepsilon_p N_f^{0.66} = 1.02 \quad (2)$$

$$\text{Material S} \qquad \Delta\varepsilon_p N_f^{0.65} = 1.17 \quad (3)$$

Figure 8 shows the calculated fatigue life curves by Eq.(2) and (3) together with the observed fatigue life. Eq.(2) and (3) give a good prediction for the actual fatigue life under mean strain for both materials. From these results, it could be concluded that the low cycle fatigue lives of the specimen failed in the surface fracture mode under mean strain are primarily controlled through the effect of mean strain on the small crack growth.

CONCLUSIONS

Low cycle fatigue test and small crack propagation test were conducted on the two kinds of annealed low carbon steel having the fine and coarse grained microstructures to make clear the influence of grain size and mean strain on the low cycle fatigue life and on the fracture mode transition. The following conclusions can be drawn through this study,

(1) A surface to internal fracture mode transition becomes easy to occur with an increase in a mean strain and in a grain size.
(2) The fatigue life of a specimen failed in the surface fracture mode at a small plastic strain is not primarily controlled by the exhaustion of ductility. In such a regime, the characteristics of fatigue life under mean strain for both materials can be predicted by the calculation of a low cycle fatigue life on the basis of the law of small crack growth.

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Table.1 Heat treatment processes.

Material-L	1200 ℃ × 2.5 hr. furnace cool
Material-S	1200 ℃ × 2.5 hr. furnace cool 900 ℃←→750℃ Up-Down (repeat 5times) air cool

Table.2 Characterization of the materials.

Material	Grain size (μm) ferrite	Grain size (μm) pearlite	Y.S.(MPa)	T.S.(MPa)	ε f
L	62	38	229	427	0.74
S	14	8	260	471	1.06

Y.S. : Yield Stress
T.S. : Tensile Strength
ε_f : Ductility

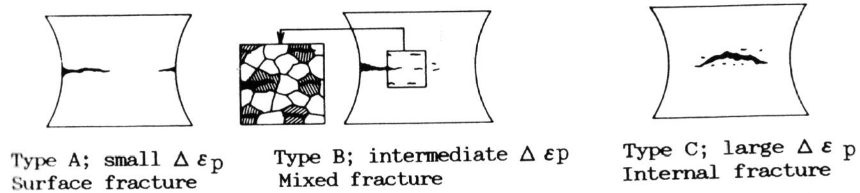


Fig.1 Schematic representation of fracture mode transition with increase in $\Delta\varepsilon_p$ in a low carbon steel.

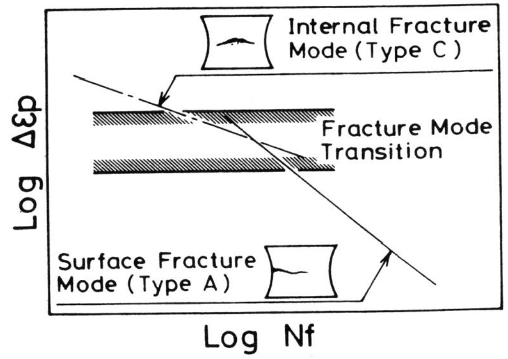
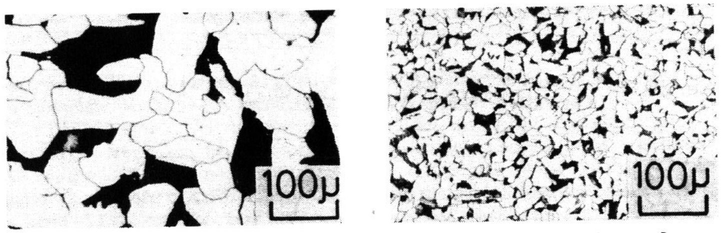


Fig.2 Schematic diagram illustrating the two failure limit lines.



(a) Coarse grained steel. (b) Fine grained steel.

Fig.3 Microstructure of the materials.

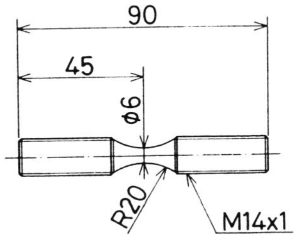
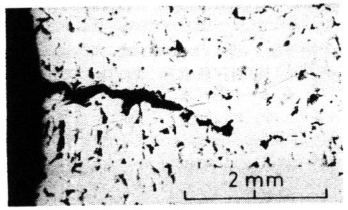
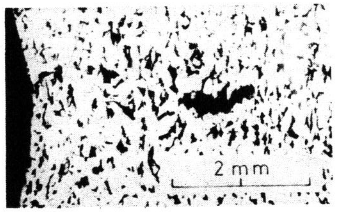


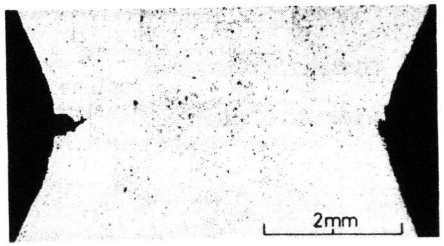
Fig.4 The specimen configuration.



(a) Coarse grained steel
(ε_m= 0.35, $\Delta\varepsilon_p$= 0.03)
Surface fracture mode

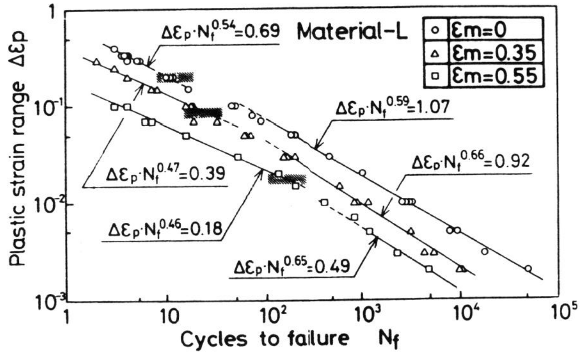


(b) Coarse grained steel
(ε_m= 0.35, $\Delta\varepsilon_p$= 0.15)
Internal fracture mode

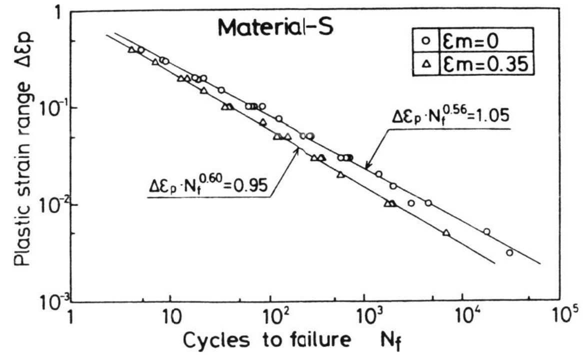


(c) Fine grained steel (ε_m= 0.35, $\Delta\varepsilon_p$ = 0.3)
Surface fracture mode

Fig.5 Fracture mode transition observed in low cycle fatigue under mean strain for coarse and fine grained steel.

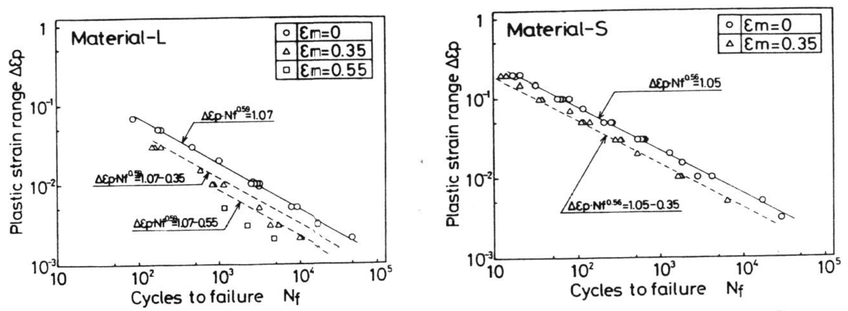


(a) Coarse grained steel.



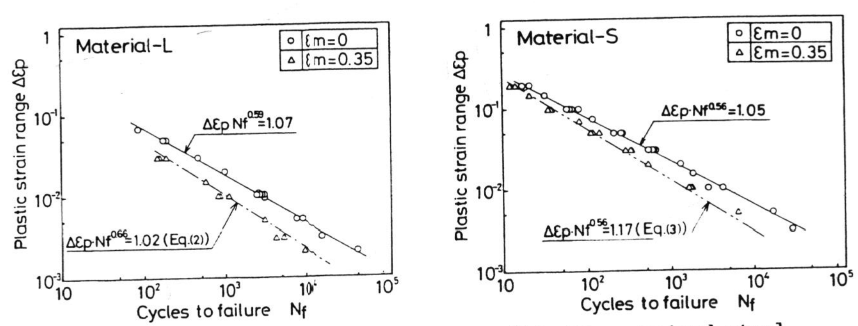
(b) Fine grained steel.

Fig.6 Effect of fracture mode transition on low cycle fatigue behaviors.



(a) Coarse grained steel. (b) Fine grained steel.

Fig.7 Comparison of Eq.(1) with fatigue test results.



(a) Coarse grained steel. (b) Fine grained steel.

Fig.8 Comparison of calculated life curves with experimental fatigue life for the surface fracture mode.