Fatigue Crack Growth Behavior in Ultrafine Grained Low Carbon Steel

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Ultrafine grained (UFG) low carbon (0.15 wt.% C) steel produced by equal channel angular pressing (ECAP) was tested for investigating the effect of load ratio on the fatigue crack growth rate. Fatigue crack growth resistance and threshold of UFG steel were lower than that of as-received coarse grained steel. It was attributed to the less tortuous crack path. The UFG steel exhibited slightly higher crack growth rates and a lower ΔK_{th} with an increase of R ratio. The R ratio effect on crack growth rates and ΔK_{th} was basically indistinguishable at lower load ratio (R>0.3), compared to other alloys, which indicates that contribution of the crack closure vanishes. The crack growth rate curve for UFG steel exhibited a longer linear extension to the lower growth rate regime than that for the coarse grained as-received steel.

Key Words: Ultrafine Grained Materials, Fatigue Crack Growth, Crack Closure Effective Stress Intensity Range

1. Introduction

The mechanical behavior of nanocrystalline and ultrafine grained (UFG< 1 μm) materials has been a subject of great interest in recent years due to their high tensile strength with fairly large ductility, hardness, and superplasticity (Berbon, 1999 ; Park 2000 ; Valiev 1994). Such properties are, however, not always ensuring for engineering alloys. In order to consider the UFG materials for successful engineering applications, their fatigue properties should be examined.

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There have been a limited number of studies on the fatigue behavior of UFG materials, and Those have been mainly focusing on cyclic hardening or softening behavior with Bauschinger energy parameter, fatigue slip band and low-and high-cycle fatigue lifetimes for copper and aluminum alloys (Agnew, 1998; Agnew, 1999; Patlan, 2001; Rabinovich, 1995). The UFG materials are known to exhibit a higher crack growth rate, which may lead to a reduction in the low-cycle fatigue life (Rabinovich, 1995). Also, they are expected to have a higher resistance to crack nucleation, which leads to increase in high-cycle fatigue life and endurance limit (Rabinovich, 1995). This is due to the fact that grain refinement tends to homogenize the localized deformation, which causes crack initiation, within a grain. Thus, the possibility of crack initiation is reduced, and consequently greater crack nucleation resistance can be exhibited. However, conflicting results were obtained in the fatigue property estimation. For example, the aluminum alloy produced by equal channel angular pressing (ECAP) exhibited a longer high-cycle fatigue life while no improvement in the fatigue endurance was observed (Patlan, 2001). Another fine grained aluminum alloy showed a shorter low-cycle fatigue life with some amount of improvement in the fatigue endurance (Rabinovich, 1995). This discrepancy might be partly due to processing methods and further thermomechanical treatment and structural parameters such as crystallographic texture and substructure. To date, however, no fatigue crack propagation behavior of the ECAPed ultrafine grained material has been characterized.

The purpose of this study is to investigate the effect of load ratio on the fatigue crack growth rate of UFG low carbon (0.15 wt.%C) steel produced by equal channel angular pressing. We attempt to provide information about the fatigue crack growth behavior of the ultrafine grained low carbon steel for further development towards its practical applications.

2. Experimental Procedure

Four passes ECAP was carried out at 623 K using samples of commercial low carbon steel (Fe-0.15%C-0.25%Si-1.15Mn (in wt.%)). ECAP experiments were documented in detail in the earlier reports (Park 2000). A nearly equiaxed UFG microstructure was obtained. The subsequent annealing treatment was conducted at 753 K for 72 hours in order to make recovery nearly completed and recrystallization active. The grain size of as-received and the UFG sample (annealed for 72 hours) was ~30 and 0.5 μm, respectively. Figure 1 represents TEM micrograph of ferrite phase of the UFG sample annealed for 72 hours.

Constant load amplitude fatigue crack growth experiments were carried out on the single edge-notched (SEN) sample with the thickness of 2.7 mm, the width of 15 mm and the length of 110 mm using Instron 8511 servo-hydraulic testing machine. The specimens were testes under load ratio $R=\sigma_{min}/\sigma_{max}=0.1$, 0.3 and 0.5 at a frequency of 20 Hz.

Fig. 1 TEM micrograph showing the microstructure in ultrafine grained low carbon steel annealed for 72 hrs at 753 K

The stress intensity factor for the SEN sample was calculated using the following equation :

$$K=\left(\frac{P}{Wt}\right)(\pi a)^{0.5}\left\{1.12-0.231\left(\frac{a}{W}\right)+10.55\left(\frac{a}{W}\right)^2-21.72\left(\frac{a}{W}\right)^3+30.39\left(\frac{a}{W}\right)^4\right\} \quad (1)$$

where W, t and a are the width and the thickness of specimen and the crack length, respectively.

A traveling microscope with a magnification of 50 was used for measuring crack length. For a crack closure test, the unloading elastic compliance method was adopted. Multiple strain gages were placed in the path of the crack to the specimen. The crack opening load, P_{op}, was approximated at $\Delta K \sim 15$ MPa$\cdot$m$^{0.5}$ as the point of first deviation from linearity in the elastic compliance curve upon unloading at three load ratios $R=0.1$, 0.3 and 0.5 (Elber, 1970).

3. Results and Discussion

3.1 Tensile strength

Stress-strain curves of the as-received and ECAPed ultrafine grained samples are shown in Fig. 2. The as-received sample exhibited the typical strain hardening behavior with large elongation. As similar to other ultrafine grained materials (Valiev, 1994), the tensile deformation behavior of the present UFG low carbon steel was characterized by ultrahigh strength and the

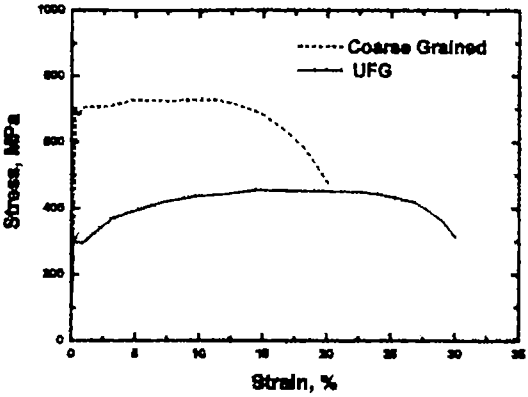

Fig. 2 Stress-strain curves of coarse grained and UFG low carbon steel

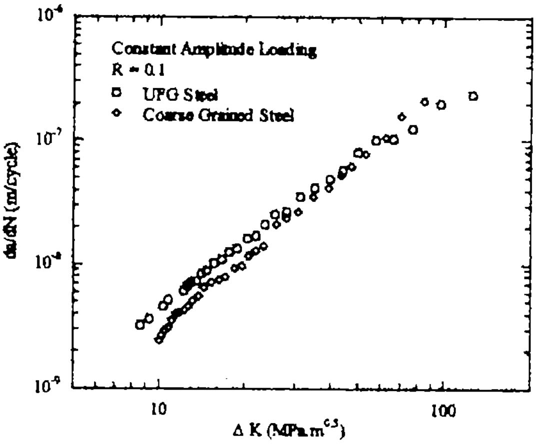

Fig. 3 A comparison of fatigue crack growth behavior of coarse grained and UFG steels at R=0.1

absence of strain hardening. The ultimate tensile strength (UTS) and yield strength (YS) of the UFG sample were found to be 720 MPa and 683 MPa, respectively. In contrast, The UTS and YS of the as-received sample were 480 MPa and 310 MPa, respectively.

3.2 Effect of microstructure on fatigue crack growth

Fatigue crack growth rate curves of the coarse grained and UFG samples (annealed for 72 hours) at load ratio R=0.1 are presented in Fig. 3. Which clearly shows that the crack growth rates in the as-received coarse grained sample appear to be lower than in the UFG sample. However, the crack growth rate of the present UFG steel was lower than that of the as-received steel at $\Delta K > 60\ \mathrm{MPa \cdot m^{0.5}}$. This turnover trend of the fatigue growth curves is similar to that reported for other UFG material (Vinogradov, 1999). This is partially due to the fact that, in general, the effect of roughness-induced crack closure is significant at low ΔK values, whereas the effect is reduced at high ΔK values (Cho, 1996; Vinogradov, 1999). And, this trend is expected to be significant particularly for coarse grained materials. It results in the lower crack growth rate of the UFG steel at $\Delta K > 60\ \mathrm{MPa \cdot m^{0.5}}$, compared to coarse grained materials. Further investigation on quantitative crack closure effect with crack propagation is required.

Fine grained materials are known to exhibit lower resistance of fatigue crack growth, compared to coarse grained materials. It has been explained in view of intrinsic factors such as reverse plastic zone size (Rabinovich, 1995) and extrinsic factors such as roughness-induced crack closure (Vinogradov, 1999). Because the plastic deformation zone in the fine grained materials is normally larger than grain size, a reverse slip of the dislocations during unloading is difficult so that the accumulation of damage is large during cycling. In addition, the less tortuous crack path induced during fatigue crack growth cannot decrease the driving force for crack advance effectively and cause a less roughness-induced closure, and consequently leads to a higher fatigue crack growth rate in the fine grained materials (Rabinovich, 1995; Vinogradov, 1999). Thus, all of these effects lead to decrease in threshold and reduction of the crack growth rate as the grain size is decreased. It is consistent with the present investigation results, similar to those observed for other UFG materials (Rabinovich, 1995; Vinogradov, 1999). The lower threshold and higher fatigue crack growth rates were observed in the UFG steel, which had much finer grain size than the as-received steel.

It also shows that the coarse grained steel has somewhat higher ΔK_{th} value in the stage I regime of the curves, indicating that the onset of fatigue crack growth is more difficult for the coarse grained microstructures. Despite the marked difference in the monotonic constitutive behavior (Fig. 2) due to grain refinement, there is little difference in the fatigue crack growth behavior. It implies that grain refinement does not appear to enhance the fatigue crack growth resistance of the low carbon steel.

3.3 Effect of load ratio on fatigue crack growth

Fatigue crack growth rates of the coarse grained and UFG samples in a function of stress intensity factor range are shown in Fig. 4 at three load ratios of R=0.1, 0.3 and 0.5. In case of the UFG samples, as shown in Fig. 4, the crack growth rates increase and threshold intensity factor range, ΔK_{th}, seems to decrease with increasing R, even though the growth rate curves do not reach threshold levels experimentally. Such load ratio dependent behavior has been widely observed and can generally be explained by crack closure effects, which predominates at low ΔK levels (Vinogradov, 1999). However, the load ratio effect on ΔK_{th} and growth rates is much less pronounced at R=0.1 and 0.3, as shown in Fig. 5, compared to other alloys (Boyce, 2001). Especially, the load ratio effect was indistinguishable at R=0.3 and 0.5. In the stage II regime of the growth rate curves, the crack growth behavior at three load ratios apparently conforms to the Paris law as follows:

$$da/dN = C(\Delta K)^m \quad (2)$$

The values of the constants, C and m were calculated from the stage II regime of the curves and summarized in Table 1.

As mentioned earlier, compliance curves were determined from near tip strain gage measurement for the UFG steel at three different ratios. Figure 5 shows quite clearly that the crack closure ratios ($U=\Delta K_{eff}/\Delta K$) increase with the load ratio increase, indicating that closure effect decreases as R increases. The effective stress intensity range was defined as $\Delta K_{eff}=K_{max}-K_{op}$, where K_{op} is the crack opening stress intensity factor. The value of crack closure ratio U at R=0.3 is similar to that at R=0.5, as shown in Fig. 5, which results in the fact that the load ratio effect on crack growth rate was indistinguishable when

Table 1 Results of regression of da/dN versus ΔK plots

Material	R	C (m/cycle)	m
As-received	0.1	2.6×10^{-11}	2.02
UFG	0.1	9.9×10^{-11}	1.67
UFG	0.3	1.4×10^{-10}	1.62
UFG	0.5	1.2×10^{-10}	1.69

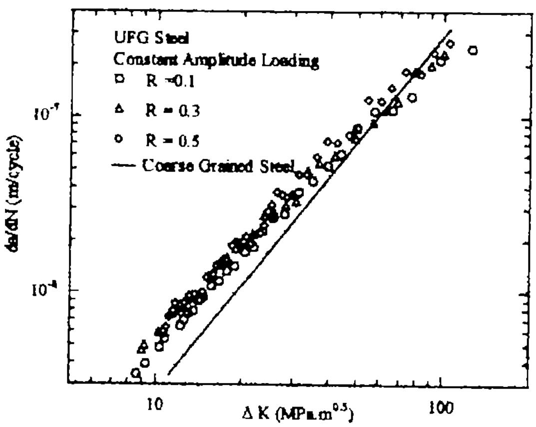

Fig. 4 Effects of stress ratio on the fatigue crack growth behavior of UFG steel

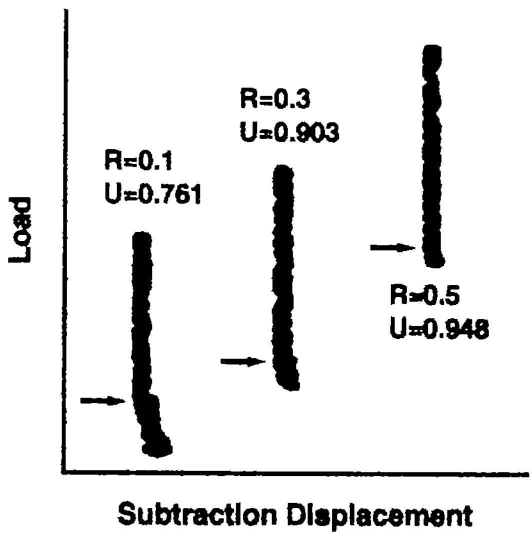

Fig. 5 Load versus subtraction displacement determined from near tip strain gage measurement in fatigue tests of UFG steel

$R>0.3$. The UFG steel exhibited slightly higher crack growth rates and a lower ΔK_{th} with an increase in R ratio, as mentioned earlier. The R ratio effect on growth rates and ΔK_{th} is generally much less pronounced at $R>0.5$ or 0.7 (McEvely, 1998). However, for the UFG steel, growth rates are basically indistinguishable at $R>0.3$. This can be explained by the fact that finer grained materials usually produce a relatively less serrated crack path, and correspondingly lower the opening load Pop. Thus, corresponding Kop is lower and consequently Kmin can reach Kop readily with smaller increment of load ratio during a constant loading amplitude fatigue experiment, indicating that contribution of the crack closure vanishes. Thus, the observed load ratio effect in most of the crack growth region in the UFG steel might be due to crack closure.

Crack growth rates are replotted in Fig. 6 as a function of ΔK_{eff}. Although there is some uncertainty in application of a fixed constant closure ratio to varied ΔK values, the difference in crack growth rates became significantly smaller, indicating that crack closure was responsible for the load ratio effect. Indeed, the crack closure ratios increase with ΔK, which is characteristic in metals of a roughness-induced crack closure mechanism associated with the fracture surface asperities.

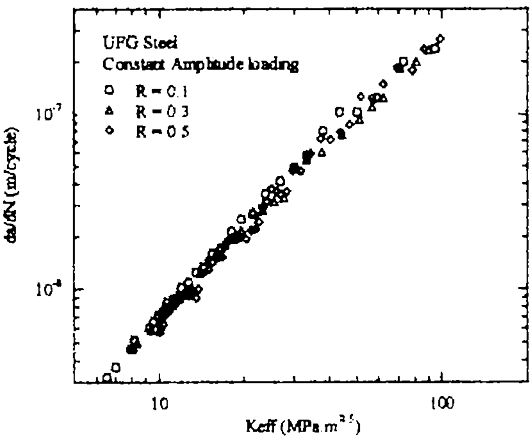

Fig. 6 Fatigue crack growth data plotted in terms of ΔK_{eff} for UFG steel

3.4 Fatigue crack paths

Crack paths for the coarse grained and UFG samples with three different load ratios were observed by using optical microscope. The crack paths for the coarse grained and UFG samples at $R=0.1$ are shown in Figs. 7(a) and (b), respectively. In the UFG specimen the crack propagates straight with very small deflections while in the as-received specimen the crack grows in a zigzag manner, as shown in Figs. 7(a) and (b). For the UFG steel, such smooth surfaces might induce a higher fatigue crack growth rate by reducing roughness-induced crack closure effect, compared to the coarse grained steel.

(a) (b)

Fig. 7 Optical micrographs of the fatigue crack growth paths for coarse grained (a) and UFG (b) steel

3.5 Transitions in fatigue fracture mode

It has been established that the transition from the near-threshold regime to the intermediate stage of fatigue crack growth accompanies a change from a microstructure-sensitive to a microstructure-insensitive fracture behavior (Ritchie, 1988). Transitions in fatigue fracture mode from the slow growth rate regime to the intermediate stage typically occur when the reverse crack tip plastic zone size (r_p) becomes of the same order as the material's grain size (Ritchie, 1988). The reverse plastic zone size (r_p) under plane stress condition is defined by (Suresh, 1991)

$$r_p = \left(\frac{1}{10\pi}\right)\left(\frac{\Delta K}{\sigma_{ys}}\right)^2 \qquad (3)$$

where ΔK is the stress intensity factor range, and σ_{ys} is the yield strength. As shown in Fig. 3, there is a 'knee' in the growth rate curve for the coarse grained steel, however, the existence of a 'knee' is not apparent in the UFG steel. It is interesting to note that a 'knee' in the growth rate curve for the as-received steel might be associated with the reverse plastic zone size. The 'knee' in the growth rate curve for the as-received steel is expected to occur at $\Delta K \sim 9.5\ \mathrm{MPa \cdot m^{0.5}}$, based on a $\sigma_{ys} = 310$ MPa and grain size $= 30\ \mu$m for the coarse grained steel. The value of $9.5\ \mathrm{MPa \cdot m^{0.5}}$ is similar to the observed stress intensity range ($\sim 12\ \mathrm{MPa \cdot m^{0.5}}$). However, for the UFG steel, there is no change in the growth rate curve. The reverse crack-tip plastic zone in the observed Paris-law ΔK regime ($8.6 \leq \Delta K \leq 100\ \mathrm{MPa \cdot m^{0.5}}$) was estimated to be greater than at least 5 μm in the UFG steel, based on a $\sigma_{ys} = 683$ MPa. Thus, the crack-tip plastic zone was much larger than the grain size of UFG samples ($= 0.5\ \mu$m). A large reverse plastic zone permits the crack to interact with several grains during cyclic loading. This condition allows for the simultaneous formation of planar slip bands in several grains, thereby resulting in a macroscopically flat fracture surface, as shown in Fig. 7 (b). Thus, the crack growth curve for the UFG steel can be extended linearly to the lower growth rate regime than that for the coarse grained steel.

Assuming crack growth per cycle to be proportional to Δ crack tip opening displacement (CTOD), a Paris law is described by the equation (Budianski, 1978)

$$da/dN \approx \Delta CTOD = \Delta K^2 / 4\sigma_y E \qquad (4)$$

where ΔK, σ_y, E are the stress intensity factor range, the yield strength, and the Young's modulus, respectively. Much higher yield stress due to grain refinement causes smaller ΔCTOD of fatigue cracks under the same stress intensity factor condition. This may in turn lead to an increase in the resistance of crack growth rates in the present UFG steel.

On the basis of the obtained results it is difficult to evaluate quantitatively the effects of the factors mentioned previously, such as the crack path deflection in combination with the roughness-induced crack closure, the yield strength, and the plastic zone size, on the fatigue crack growth resistance of the present UFG steel. The beneficial effect of reduction in ΔCTOD due to a higher yield strength seems to be weaker than detrimental effect of the crack path deflection in combination with roughness-induced crack closure and plastic zone size on the fatigue crack growth resistance of the present UFG steel. Accordingly, the higher fatigue crack growth rate in the present UFG steel, similar to that of other UFG alloy (Vinogradov, 1999), may arise from smoother fracture surfaces and relatively larger reverse plastic zone to grain size.

4. Conclusions

Ultrafine grained low carbon (0.15 wt.% C) steel produced by equal channel angular pressing (ECAP) was tested for investigating fatigue crack growth behavior. Especially, emphasis is placed on investigating the effect of load ratio on the fatigue crack growth rates of UFG microstructure. The present investigation of crack growth in UFG steel has led to the following conclusions:

(1) Fatigue crack growth resistance and threshold of UFG steel were lower than those of as-received coarse grained steel.

(2) The UFG steel exhibited slightly higher crack growth rates and a lower ΔK_{th} with an increase in R ratio.

(3) The R ratio effect on growth rates and ΔK_{th} was basically indistinguishable at much lower load ratio (R>0.3), compared to other alloys.

(4) The higher fatigue crack growth rate in the present UFG steel may arise from smoother fracture surfaces and relatively larger reverse plastic zone to grain size, compared to the as-received coarse grained steel.

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