On the Early Initiation of Fatigue Cracks in the High Cycle Regime

S. Ishihara[1], A. J. McEvily[2]
[1] *Dept. of Mechanical Engineering, Univ. of Toyama, Toyama, Japan;*
[2] *Dept. of Materials Science and Engineering, Univ. of Connecticut, CT, USA;*
E-mail: *ishi@eng.u-toyama.ac.jp*

Abstract

A series of replicas taken periodically throughout the fatigue lifetime has been used to determine the fraction of lifetime in the high cycle range at which a fatigue crack can be first identified. For the alloys investigated this fraction is less than 10% of the fatigue lifetime. The replicas also provide a record of crack length as a function of the number loading cycles, and this information has been used to compare the crack length with predictions based upon a basic constituitive relationship. Good agreement between the experimental results and the predictions was obtained.

1. Introduction

In contrast to low cycle fatigue, it is often stated that fatigue cracks initiate late in life in the high cycle regime. However our recent studies have demonstrated that fatigue cracks are also initiated early in life in high cycle fatigue. These studies involve the periodic replication of the specimen surface during a fatigue test. Once a fatigue crack is clearly identified on one of the later replicas, the earlier replicas are re-examined to determine the earliest fraction of life at which a fatigue crack can be identified. The materials thus far examined include steels, aluminum alloys, Ti-6Al-4V, and magnesium alloys, and in each of these materials 10 micron-sized fatigue cracks were found at approximately 10% of the fatigue lifetime in the 10^6 cycle lifetime range. It is also noted that Thompson, Wadsworth and Louat [1] in much earlier work observed microcracks in copper at less than 10% of the high-cycle fatigue lifetime.
Further, the information obtained can be used to compare with predicted crack growth behavior based based upon the relation

$$\frac{da}{dN} = A(\Delta K_{eff} - \Delta K_{effth})^2 \quad (1)$$

where a is the crack length, A is a material-environmental constant, $\Delta K_{\rm eff}$ is the effective range of the stress intensity factor, i.e., $K_{\rm max}$ - $K_{\rm op}$, where $K_{\rm op}$ is the stress intensity factor at the crack opening level, and $\Delta K_{\rm effth}$ is the range of the stress intensity factor at the threshold level. The marterial constant A has dimensions of MPa^{-2} so that Eq. 1 is dimensionally correct as expected by Liu [2] and Frost[3].

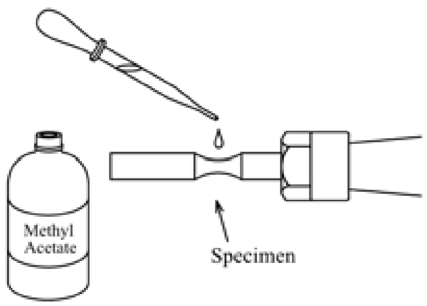
It will be shown that good agreement exists between the experimental results for the crack length as a function of he number of cycles applied and predictions based upon Eq. 1.

2. The replication procedure

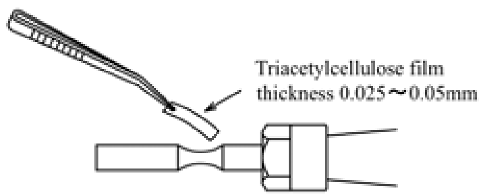
The replication procedure used in the present study is described as follows. Fatigue tests were interruped periodically (ΔN cycles), to obtain replicas of the specimen surface. After cleansing the surface with ethyl alcohol, drops of methyl acetate are applied to the specimen surface (Fig. 1(a)). Then before the methyl acetate has dried, an acetylcellulose film (Ouken Co. Ltd.) of a thickness of 0.025~0.05 mm is firmly pressed onto the specimen surface. (Fig. 1(b)).

After allowing the acetylcellulose film to dry (3~5 minutes), it is peeled away carefully from the specimen surface using pincers. The collected replicas are then mounted on a slide glass with the sspecimen-contacting side up using double-faced tape (Fig. 1(c)). The above procedure is repeated at a constant interval of cycles (Fig. 1(d)). The interval is usually 1/15~1/20 of total of fatigue life N_f. A total of 15~20 replicas are collected for one fatigue test. These replicas enable us to measure the crack length at each of the fatigue stage (Fig. 1(e)).

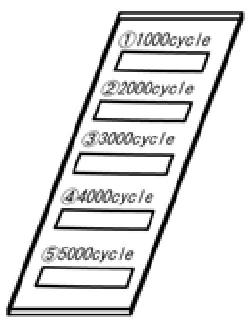
An optical microscope (ORYMPUS-BX51M) is used to examine the replicas. Once a fatigue crack is clearly identified on one of the later replicas, the earlier replicas are re-examined to determine the earliest fraction of life at which a



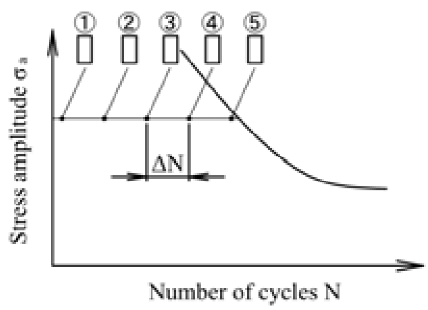
(a)



(b)



(c)



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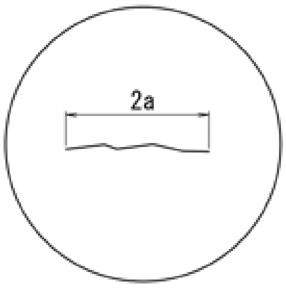
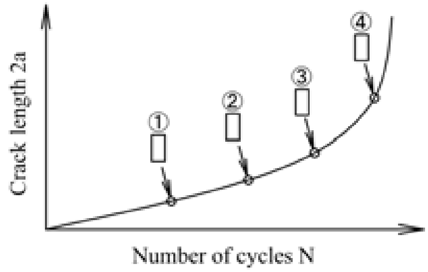




(e) (f)

Fig. 1 The replication procedure used in the present study.

fatigue crack can be identified. Photos of the crack were taken using a camera system, DP12.

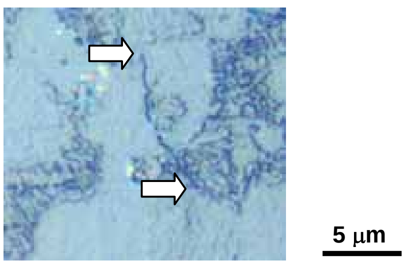
The crack propagation curve, i.e., the relation between crack length 2a vs. number of cycles, N can be constructed by plotting the crack lengths measured as a function of number of cycles N (Fig. 1(f)). For more detailed study, the replicas can be coated and observed using a scanning electron microscope.

3. Applications and Experimental Results (early detectioin)

Crack initiation and propagation behaviour of polished, unnotched rotating beam (R = -1) specimens in four different alloy systems (a steel, an aluminum alloy, a titanium alloy and a magnesium alloy) were investigated using the above replication technique to determine how early cracks could be detected as well as to deterrmine their crack growth behavior during the fatigue process.

a. Steels [4]

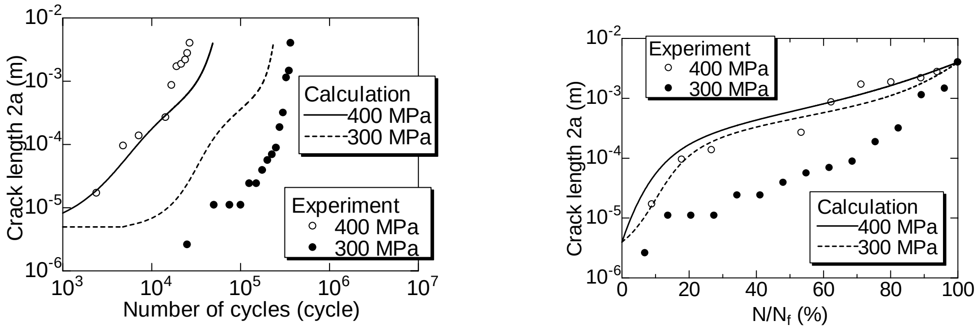
Figure 2 shows a crack in the carbon steel JIS S45C of a length of about 10 μm that initiated at the fatigue life ratio of 14% at stress amplitude of 300 MPa. As can be seen from the figure the crack initiated within a ferrite grain



N=50400 cycles (N/N_f=14 %) 11 μm

Fig.2 Photograph showing early crack initiation in the carbon steel JIS S45C (σ_a=300 MPa, R=-1)

Figures 3 (a), and 3(b) show crack propagation curves, 2a vs. N and 2a vs. N/N_f for the carbon steel JIS S45C, where 2a indicates crack length, N is the number of cycles, and N_f is the number of cycles to failure. As seen from these figures, 10 micron-sized fatigue cracks were found at approximately 10% of the fatigue lifetime in the 10^5~10^6 cycle lifetime range. The solid and broken curves in these figures and others will be discussed later.



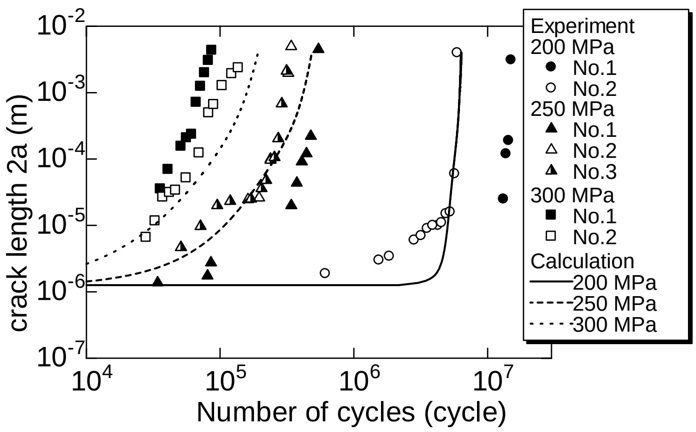
(a) 2a vs. N (b) 2a vs. N/Nf

Fig. 3 Crack propagation behavior for the carbon steel, JIS S45C.

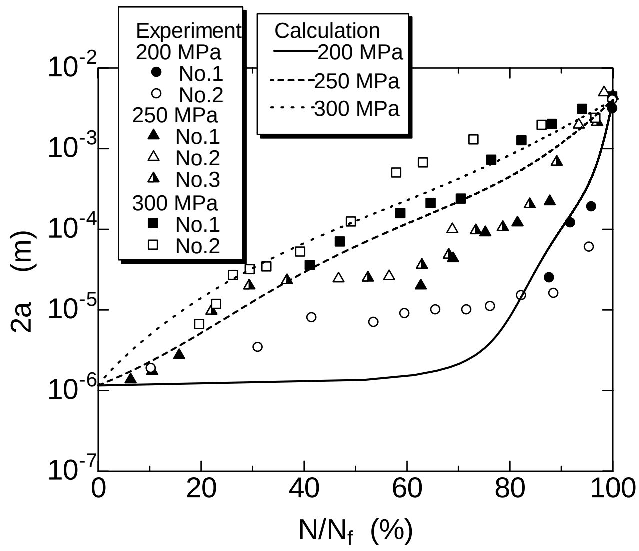
b. Aluminum alloys [5]

Figure 4(a) is for extruded aluminum alloy 2024-T3, and shows the variation of the crack length 2*a* as a function of number of cycles *N*. Figure 4(b) shows 2a vs. the fatigue life ratio N/N_f. The nominal chemical composition is Cu:4.25, Mg: 1.32, Mn: 0.56, Zn: 0.25, Fe: 0.12, Al: bal. wt(%). The mechanical properties of the Al alloy are a yield Strength of 420 MPa, atensile strength of 570 MPa, and an elongation of 17 %.

As shown in Fig. 4(a) and (b), micro-cracks 1.4 μm in length were observed at 5-6 % of the fatigue life ratio at the stress amplitudes of 122.5 and 140 MPa. The total fatigue life can therefore be considered to have been spent in crack propagation with very little error.



(a)2a vs. N



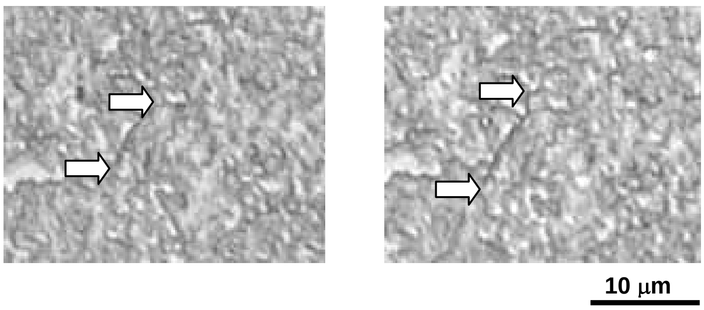
(b) 2a vs. N/N_f

Fig. 4 Variation of crack length during the fatigue process for the extruded Al-2024.

c. Ti-6V-4Al [6]

The Ti-6Al-4V alloy used was a commercially extruded alloy of the following composition (wt. %): 6.21 Al, 4.05 V, 0.16 Fe, 0.15 O, 0.01 C, 0.01 N and Ti bal. The alloy had yield strength of 860 MPa, a tensile strength of 1012 MPa and an elongation of 11 %. Figure 5(a) and (b) show a crack with a length of less than 10 μm that initiated at a fatigue life ratio of 20% at a stress amplitude of 740 MPa.

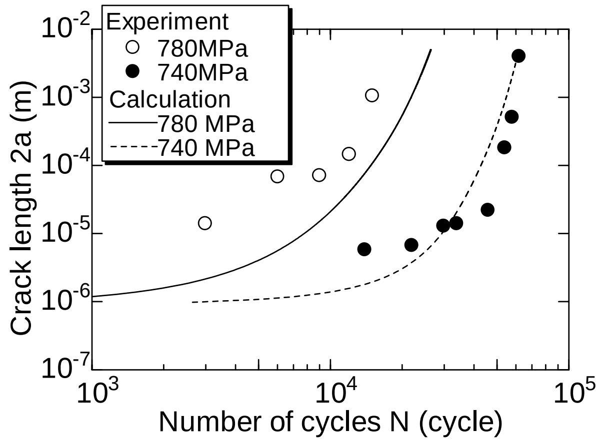
Figure 6 shows crack propagation curves, crack length 2*a* vs. number of cycles *N*, for two stress amplitudes of 740 MPa and 780 MPa. Again, as seen from the figure, fatigue cracks initiated early stage in the fatigue life.



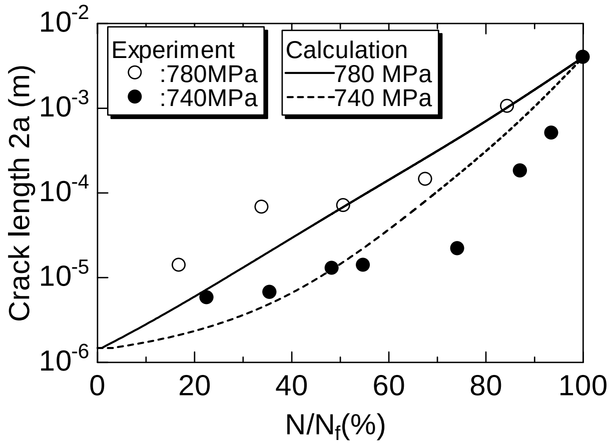
(a) N/N_f=22.5 % 6.2 μm 13940 cycles

(b) N/N_f=35.5 % 7 μm 21950 cycles

Fig. 5 Successive observations on a specimen surface during the fatigue process at stress amplitude of 740 MPa.



(a) 2a vs. N



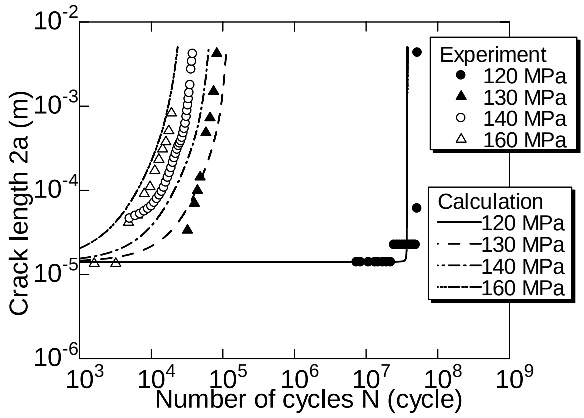
(b) 2a vs. N/N_f

Fig. 6 Short fatigue crack propagation behavior in Ti-6Al-4V alloy for two different stress amplitude in laboratory air.

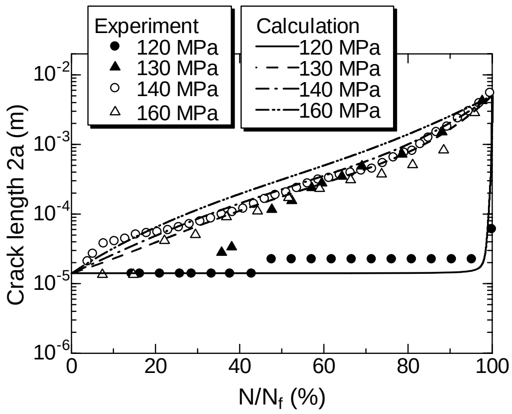
d. Magnesium alloy [7]

The magnesium alloy AZ31 in the etruded condition was used in this investigation. Its chemical composition is Al; 2.5~3.5, Zn; 0.7~1.3, Mn; 0.2, Fe; 0.005, Si; 0.05, Ca; 0.04, wt(%). A cylindrical billet of 200 mm diameter was extruded into a round bar with a diameter of 70 mm, an extrusion ratio of 10. The alloy had a yield strength of 200 MPa, a tensile strength of 275 MPa and an elongation of 11 %.

The variation of the crack length, 2a, as a function of number of cycles N is shown in Fig. 6(a) for stress amplitudes of 120~160 MPa. Figure 6(b) shows the relation 2a vs. fatigue life ratio, N/N_f. As can be seen from the figure, cracks initiated at early, 5-10 % of fatigue life.



(a) 2a vs. N



(b) 2a vs. N/N_f

Fig.7 Crack propagation curves under different stress amplitude at *R* = -1.

Table 1 summarizes the minimum crack length observed and the value of N_i/N_f for the four materials tested. As can be seen from the table, at 5~10% of the fatigue lifetime (N_i/N_f), cracks of length 5~10 μm had initiated during for the four different materials.

Table 1 Summary of the crack initiation lives for the four metals investigated.

Materials	Minimum crack length observed	**Ratio of crack initiation lives Ni/Nf**
Steel JIS S45C	**5~10 μm**	**5%**
Aluminum alloy 2024	**1~2 μm**	**5%**
Titanium alloy Ti-6Al-4V	**5 μm**	**10~15%**
Magnesium alloy AZ31	**10 μm**	**5%**

4. Analysis

It is noted that a standard linear elastic fracture mechanics (LEFM) analysis is not applicable to short fatigue crack propagation behavior for the following reasons:

a. In the very short fatigue crack propagation range the stress for propagation is controlled by the endurance limit of the material rather than by the long crack threshold condition.

b. In the short crack regime small scale yielding conditions are not applicable, and a modification for elastic-plastic conditions is needed.

c. Crack closure in the wake of a newly formed crack is zero, but as the crack grows, the crack closure level increases to the level associated with a macroscopic crack in a distance of the order of 1 mm.

The constitutive relation for fatigue crack propagation, Eq. (1) will provide the basis for the analysis:

Equation (1) has been modified [8] to take into account the above three attributes of fatigue crack propagation:

With these modifications, Eq. (1) is written as:

$$\frac{da}{dN} = A[(\sqrt{2\pi r_e F} + Y\sqrt{\pi a F})\Delta\sigma - (1 - e^{-k\lambda})(K_{op\max} - K_{\min}) - \Delta K_{effth}]^2 \qquad (2)$$

where r_e is a material constant defined as $(\frac{\Delta K_{effth}}{\Delta\sigma_{EL}})^2[\frac{1}{2\pi F(1+\sqrt{2}Y + 0.5Y^2)}]$. This constant provides a link between the endurance limit σ_{EL} (or the fatigue strength at 10^7 cycles) and the effective threshold level. The value of r_e is of the order of 1 μm. F is given as $\frac{1}{2}(\sec\frac{\pi}{2}\frac{\sigma_{\max}}{\sigma_Y} + 1)$, and accounts for elastic-plastic behavior. Y is a geometrical constant which, for example, is equal to 0.73 for a semicircular surface flaw. $\sigma_{\max}$ is the maximum stress. The material constant k is an indicator of the rate of development of crack closure. The symbol λ represents the distance a new crack has grown. In the case of a smooth specimen it would correspond to the semi-length of a semi-circular surface flaw. In the case of a notch it would be the distance measured from the tip of the notch. K_{opmax} is the crack closure level associated with a macroscopic crack.

Equation (2) can be written in compact form as

$$\frac{da}{dN} = AM^2 \qquad (3)$$

where M, the net driving force for fatigue crack propagation, is the quantity within brackets in Eq. (2). The rates of fatigue crack propagation in the four different materials, steel, aluminum alloy, Ti alloy and Mg alloy were analyzed as a function of the M parameter. The values of parameters used for calculating M are listed for the four materials in Table 2.

By integrating Eq. (3) from r_e to a critical crack length, the relation 2a vs. N as well as the relation 2a vs. N/N_f can be predicted on the assumption that the crack initiation lives are negligible as compared to the crack propagation lives. The predicted results are drawn in Figs. 3, 4, 6 and 7. As can be seen from these figures, they show good agreement with the experimental results.

Table 2 Values of the parameters used for calculation of M.

	K_{opmax}	ΔK_{effth}	k	r_e	σ_Y	σ_{W0}
Steel JIS S45C	3 $MPam^{1/2}$	3 $MPam^{1/2}$	10000 m^{-1}	1.98 μm	660 MPa	265 MPa
Aluminum alloy 2024	4.0 $MPam^{1/2}$	1.4 $MPam^{1/2}$	16000 m^{-1}	0.72 μm	420 MPa	200 MPa
Titanium alloy Ti-6Al-4V	2 $MPam^{1/2}$	2.7 $MPam^{1/2}$	13000 m^{-1}	0.44 μm	865 MPa	710 MPa
Magnesium alloy AZ31	1.3 $MPam^{1/2}$	1.15 $MPam^{1/2}$	8000 m^{-1}	1.07 μm	206 MPa	125 MPa

5. Conclusions

A series of replicas taken periodically throughout the high-cycle fatigue lifetime has been used to determine how early a fatigue crack can be detected and also to determine the fatigue crack growth behavior. The findings are summarized as follows:

(1) The replica method is found to be useful in the detection of small cracks and in the study of their propagation behaviour during fatigue process.

(2) For the four types of alloys investigated the fraction of the crack initiation lives are generally less than 10% of the fatigue lifetime, so that the total fatigue lifetime can be considered to be the crack propagation lifetime.

(3) The replicas also provide a record of crack length as a function of the number loading cycles, and this information has been used to compare the crack length with predictions based upon a basic constituitive relationship. Good agreement between the experimental results and the predictions was obtained.

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