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# FATIGUE FRACTURE TOUGHNESS AND FATIGUE CRACK PROPAGATION IN 5.5% Ni STEEL AT LOW TEMPERATURE

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## INTRODUCTION

Recent advances in the application of a fracture mechanics approach have been extended to a quantitative analysis to the prevention of structural fatigue failure using a plane strain fracture toughness $K_{1c}$.

On the other hand, for design against fatigue, the importance of the fatigue fracture toughness $K_{fc}$ has been proposed by T. Yokobori [1, 2] and a recent experimental investigation revealed that the fatigue fracture toughness for high strength tempered martensitic steel [3] was only about half of that of usual fracture toughness. This means that $K_{fc}$, not $K_{1c}$, should be taken into consideration against fatigue design since the critical flaw size in fatigue condition predicted from $K_{fc}$ would be about one quarter comparing with that in static condition.

It is also found that a very sharp toughness transition of $K_{fc}$ is observed at about 123 K (-150° C) for this steel [3]. Namely $K_{fc}$ is drastically reduced within a fairly sharp temperature interval (hereafter this temperature is referred as FTT) and decreases further with decreasing temperature below FTT.

It is therefore necessary to consider the FTT and $K_{fc}$ as important parameters in designing structural parts and machine elements suffering fatigue loading at low temperature in order to prevent catastrophic fatigue fracture.

The object of the present investigation is to study much more thoroughly the fatigue crack propagation in 5.5% Ni steel with special interest for its difference between above and below the FTT.

## MATERIAL AND EXPERIMENTAL PROCEDURE

The material used is 5.5% Ni steel developed for use at low temperature. Because of the high toughness of this steel, more detailed fatigue behaviours at low temperature can be observed. The chemical analysis and mechanical properties of the material are shown in Tables 1 and 2 respectively.

Fracture toughness tests and fatigue tests were performed with compact tension specimen of the geometry illustrated in Figure 1. The stress intensity factor was calculated using following equation [4, 5],

$$K = \frac{P}{BW^{1/2}}\left[29.6\left(\frac{a}{W}\right)^{1/2} - 185.5\left(\frac{a}{W}\right)^{3/2} + 655.7\left(\frac{a}{W}\right)^{5/2} - 1017.0\left(\frac{a}{W}\right)^{7/2} + 638.9\left(\frac{a}{W}\right)^{9/2}\right] \quad (1)$$

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where $P$ = load
$B$ = specimen thickness
$W$ = specimen width measured from the loading line
$a$ = crack length measured from the loading line.

The ASTM recommended test procedure [4,5] was employed using a programme-load-controlled 100 ton universal testing machine with a cryostat having window to read the crack length. Copper-constantan thermocouple was attached to the opposite side of the notch of the specimen. Temperature was controlled by flow of liquid nitrogen as following manner; an electronic servo-controlled plunger pump installed in the liquid nitrogen vessel adjusts the flow when the thermocouple registered a temperature 0.5 K above or below the fixed temperature. With this equipment, it was possible to control the temperature of the specimen within ± 0.5 K for fracture toughness testing and ± 2 K during fatigue testing.

The details of the measurements of fatigue crack length and the determination of $K_{fc}$ were given before [3].

## EXPERIMENTAL RESULTS AND DISCUSSION

### Fatigue Fracture Toughness

The fatigue fracture toughness $K_{fc}$ is plotted as a function of the temperature in Figure 2(a) and also shown in this figure is the fracture toughness $K_c$. As a comparison, the results of high strength steel [3] is reproduced in Figure 2(b) which shows a clear toughness transition at about 123 K (-150°C). Above this temperature, FTT, values of $K_{fc}$ and $K_c$ are almost the same as each other. However, the value of $K_{fc}$ decreases drastically at FTT and much lower than that of $K_{Ic}$ at respective temperature.

In the case of 5.5% Ni steel, the toughness transition phenomena is not so remarkable as that in high strength steel, but one can also define the FTT at 123 K (-150°C) where $K_{fc}$ decreases drastically. Above the FTT, $K_{fc}$ increases with decreasing temperature, on the other hand, it seems to be decreased further with decreasing temperature, below the FTT.

Since 1-in-thick specimen does not meet the necessary thickness requirement for valid plane strain fracture toughness evaluation [4,5] even at low temperature, quantitative comparison between $K_{fc}$ and $K_{Ic}$ cannot be made.

### Fatigue Crack Propagation

A typical example of the analysis of crack propagation rate da/dN versus range of stress intensity factor $\Delta K$ is shown in Figure 3. A well known relationship is observed between log(da/dN) and log$\Delta K$ at each temperature and may be described by the following equation,

$$da/dN = A\ (\Delta K)^{\delta} \qquad (2)$$

where $A$ and $\delta$ are constants for a given material and temperature.

In order to analyze the effect of temperature on fatigue crack propagation rate, da/dN is plotted against 1/T in Figure 4, where T is absolute temperature. The fatigue crack propagation rate decreases with decreasing temperature down to around 123 K (-150°C) but increases at much lower temperature (93 K ; -180° C). The temperature at which the temperature dependence of fatigue crack propagation rate changes is just the same as that defined as the fracture toughness transition, FTT.





Such discontinuity in the temperature dependence is also found in $\delta$ of Equation (2). As shown in Figure 5 by a solid line, the value of $\delta$ increases with decreasing temperature and reaches its peak value at around 123 K (-150° C) and then the temperature dependence of $\delta$ seems to be reversed. This discontinuity again occurs at FTT. The similar results have been reported [6, 7] for 5% Ni and 9% Ni steels, as reproduced in this figure by dashed lines (The data from Reference [7] were read on the figures).

The same feature is also revealed in the fatigue life under the same loading condition versus temperature relationship.

All these behaviour are summarized in Figure 6. It can be clearly seen that da/dN, $\delta$ and number of cycles to failure, $N_f$, observed above FTT are all different to those observed below FTT. Then, different temperature dependences above and below FTT can be detected not only the fatigue fracture toughness but also fatigue crack propagation behaviours.

Tensile tests and Vee-notched Charpy test were also carried out. However, any transition behaviour cannot be detected within the temperature ranging RT to 93 K (-180° C) for this steel. Since fatigue data only show such peculiar transition phenomena at FTT, it can be conluded that fatigue is much more temperature sensitive properties than any other mechanical ones. And it is important to know about the existence of such discontinuities, since serious errors may result in extrapolating the data to lower temperature.

As for the fatigue crack propagation rate observed above FTT, apparent activation energy Q can be obtained from the slope of straight lines in Figure 4. Because of these straight lines are not parallel to each other the activation energy for crack propagation should be a function of stress intensity. A linear relationship between Q and ln $\Delta K$ is obtained as shown in Figure 7,

$$Q = U - a_1 \ln \Delta K \qquad (3)$$

where U and $a_1$ are constants.

As has been shown in Figure 5, $\delta$, above FTT, is expressed as a linear function of 1/T, then we have,

$$\delta = b_1 + a_1/(kT) \qquad (4)$$

where $b_1$ and k are constants.

These findings are well coincide with the dislocation groups dynamics theory [8] of fatigue crack propagation which predicts the following relation,

$$\frac{da}{dN} = \frac{A_1}{f^{\lambda}}\ (\Delta K)^{b_1}\ \exp\left(-\ \frac{U - a_1 \ln \Delta K}{kT}\right) \qquad (5)$$

where $A_1$, $\lambda$ are constants, k Boltzmann constant and f is cyclic frequency.

Much more experiments would be needed to describe the fatigue cracking behaviour below FTT since it is still unclear whether the temperature dependences of da/dN and $\delta$ are truly inverse or not at FTT.

## CONCLUSION

From the study on fatigue fracture toughness and fatigue crack propagation in 5.5% Ni steel at low temperature, the following conclusions are obtained.

(1) Fatigue fracture toughness decreases drastically within a fairly sharp temperature interval, FTT. The FTT of 1-in-thick 5.5% Ni steel is about 123 K (-150° C).

(2) Not only $K_{fc}$ but also all the parameters governing fatigue cracking such as da/dN, $\delta$ and $N_f$, discontinuities occur at FTT in their temperature dependence.

(3) Fatigue crack propagation above FTT is in good agreement with the dislocation groups dynamics theory of fatigue crack propagation.

(4) Fatigue cracking behaviour seems to be much more temperature-sensitive than any other mechanical properties.

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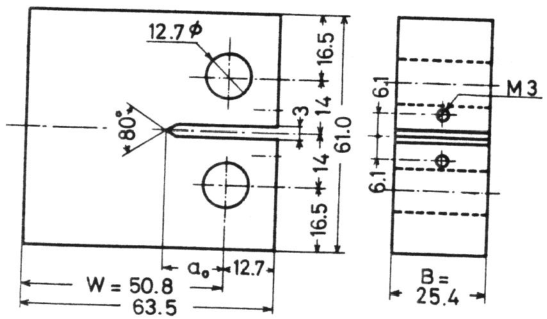


Figure 1 Compact Tension Specimen Configuration

$a_0$ = 11.2 mm for Fatigue Test
$a_0$ = 21.4 mm for Fracture Toughness Test





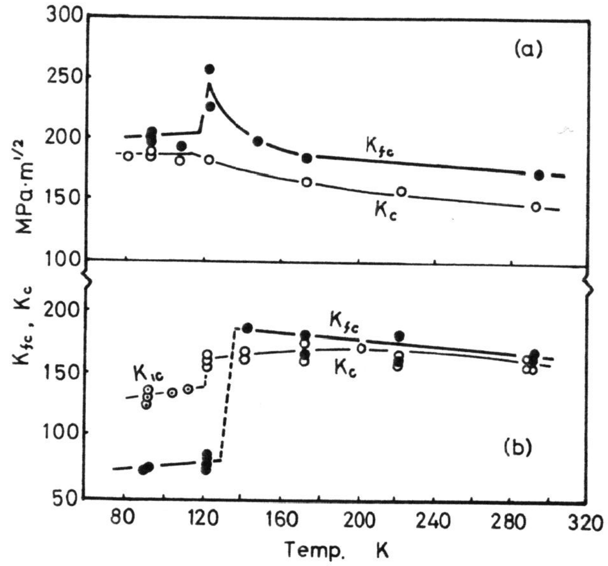


Figure 2 Fracture Toughness and Fatigue Fracture Toughness vs Test Temperature

(a) 5.5% Ni Steel
(b) High Strength Tempered Martensitic Steel [3]

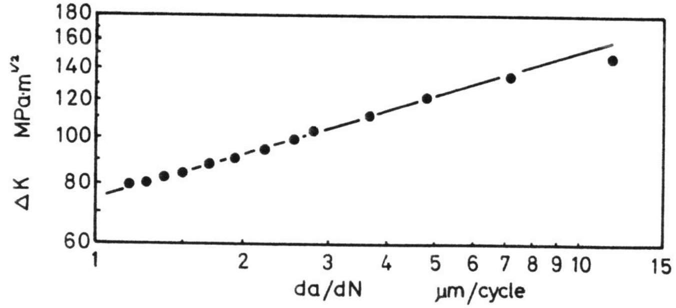


Figure 3 A Typical Example of the Plot of da/dN vs $\Delta K$. (173 K, R = 0.059)

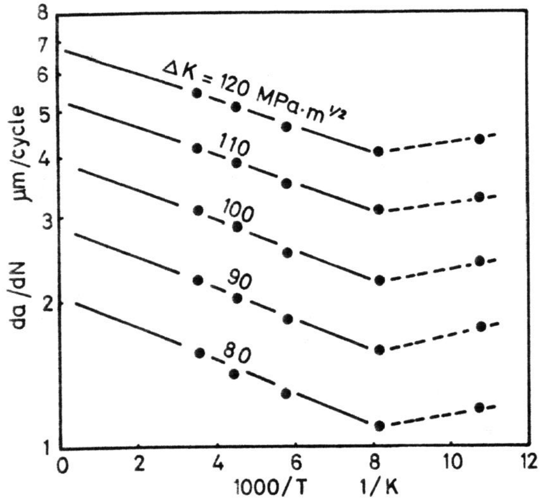


Figure 4 Fatigue Crack Propagation Rate as a Function of the Test Temperature

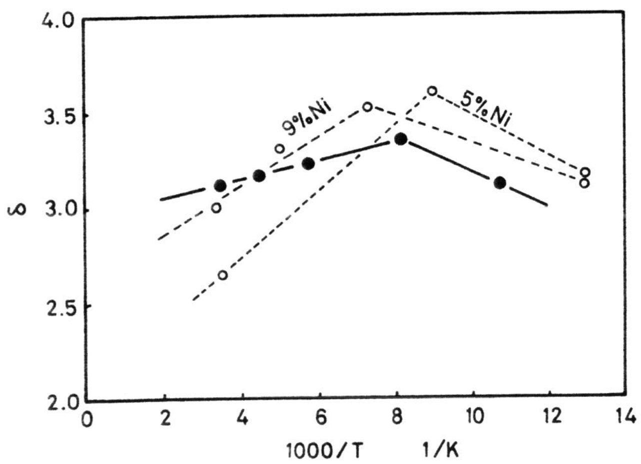


Figure 5 Experimental Relation Between δ and Test Temperature. 9% Ni ; Reference [6], 5% Ni ; Reference [7]





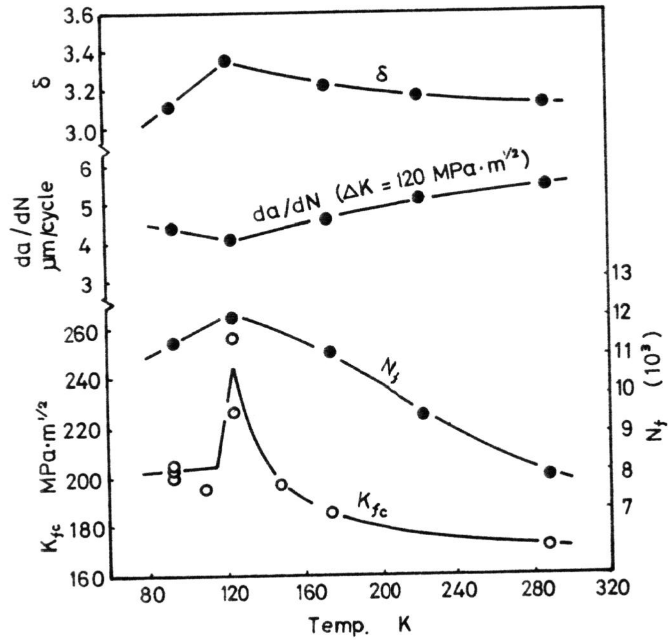


Figure 6 Fatigue Cracking Parameters and Test Temperature

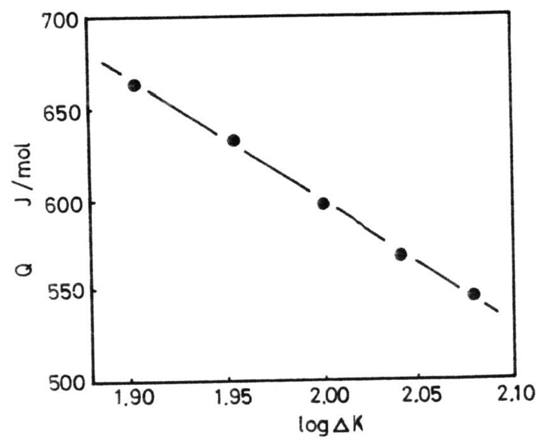


Figure 7 Variation of the Apparent Activation Energy with ΔK. ΔK ; in $MPa\cdot m^{1/2}$

Table 1 Chemical Analysis of the Material Used

| C | Si | Mn | P | S | Ni | Cr | Mo |
|---|---|---|---|---|---|---|---|
| 0.06 | 0.19 | 0.93 | 0.006 | 0.005 | 5.75 | 0.50 | 0.16 |

Table 2 Mechanical Properties of the Material Used

| Yield Pt. $\sigma_Y$ kPa | Ultimate Tensile Strength $\sigma_B$ kPa | Elong. $\varepsilon$ % |
|---|---|---|
| 59.8 | 75.5 | 30 |