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The influence of mean stress on fatigue crack propagation in dual phase low carbon steel

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In a low carbon steel, containing martensite encapsulated islands of ferrite, second-stage fatigue crack growth rate is not influenced by the mean stress. However, in steel with ferrite encapsulated islands of martensite, crack growth rate is influenced by each mean stress because its microfracture mode changes from slipping to static. An acceleration of crack growth is mainly influenced by the number of continuous cleavage facets in each matrix.

1. Introduction

The dependence of the fatigue crack propagation rate, da/dN on the stress intensity factor, $\Delta K = K_{max} - K_{min}$, is generally expressed by the relationship $da/dN = C\Delta K^m$ where C and m are constants, a is the crack length and N the number of fatigue cycles [1, 2]. However, it is said that other factors, such as microstructure, temperature, mean stress and material properties, can also influence fatigue crack growth markedly [3, 4]. The effect of microstructure is particularly important. Although there have been many investigations into such effects, there have not been enough. Previously, Richards and Lindley [5] and Ishihara [6] suggested that the general effects of mean stress and microstructure on the rate of fatigue crack propagation may be due to "static" or monotonic fracture mode which can occur in addition to characteristic striation growth. They also stated that segments of fracture in the microstructure are promoted by an increase in mean stress and lead to accelerated fatigue growth rates.

So, through appropriate heat treating procedures, two unique types of microstructure were developed successfully in low carbon steel, which is characterized by martensite encapsulated islands of ferrite (R material), and K material having ferrite encapsulated islands of martensite. The strength, toughness, ductility, etc. of such structures have been studied and their behaviour related to microstructural aspects. It has been shown that the mechanical properties of these microstructures are associated with interaction effects between these dual phases rather than with individual properties of martensite and ferrite. It has been observed in R material that fracture occurs in a brittle manner accompanying cleavage cracking of the ferrite grains.

However, crack propagation resulting in fatigue crack growth in these unique microstructures has not been explored in any detail. Because of the interesting morphological relationships which can develop between the phases, it appeared worthwhile to explore fatigue crack propagation in these two microstructures, under various mean stresses, where microstructural influence is known to be important. The characteristics of crack propagation behaviour in these dual phase microstructures under various mean stresses might be expected to show a strong dependence on microstructure. Therefore, in the present paper, attention is paid to crack growth in these dual phase microstructures. Questions arise as to how the various mean stresses in the R and K materials influence crack propagation.

2. Experimental procedure and specimens

A low carbon steel (chemical composition shown in Table I) was chosen to be investigated. After certain heat treatments, test-pieces were machined to a length of 156 mm, width of 39 mm, and thickness of 10 mm, as shown in Fig. 1 [7]. In

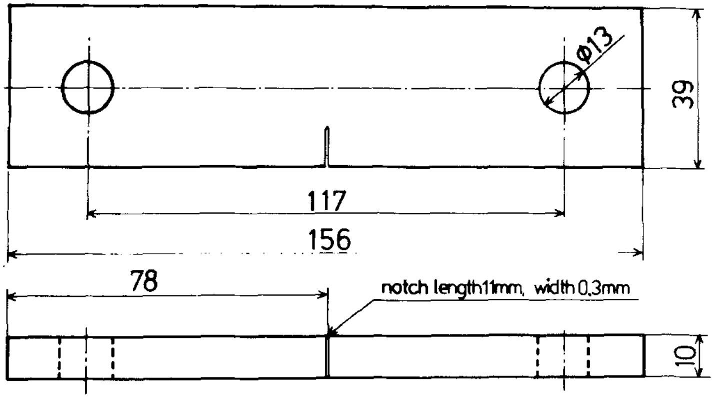

Figure 1 Geometries of the specimen used for the fatigue crack growth study.

TABLE I Chemical composition (wt%)

	C	Si	Mn	S	P	Cu	Ni	Cr
S15C	0.15	0.28	0.51	0.006	0.018	0.13	0.04	0.15

TABLE II Mechanical properties and metallurgical parameters

Material	Ferrite grain size (μm)	Martensitic structure			Reduction in area (%)	Yield stress $\sigma_{0.2}$ (MPa)	Tensile strength (MPa)
		Volume fraction (%)	Hardness (H_V 20 g)	ō (%)			
R	49	49	496	94	17	559	990
K	51	45	497	(57)	25	471	775

order to develop the desired K and R dual-phase microstructures (see Fig. 2), heat treatment was applied as shown in Figs. 3 and 4. Quantitative metallographic techniques were employed to determine the ferrite grain size, the volume fraction of martensite, the size of the martensitic structure, and the degree of connectivity* of the martensitic structure, as shown in Table II. The fatigue tests were carried out, in air, at room temperature in a hydraulic testing machine at mean stresses (σ_m) of 26, 53 and 79 MPa. The stress range ($\Delta\sigma$) was 49 MPa, with a sinusoidal wave form. The cyclic frequency was 10 Hz. Twenty electron microscope pictures were taken at the centre of the crack surface every 10 μm, following the direction of cracking.

The following equation [8] was used to calculate the stress intensity factor, ΔK:

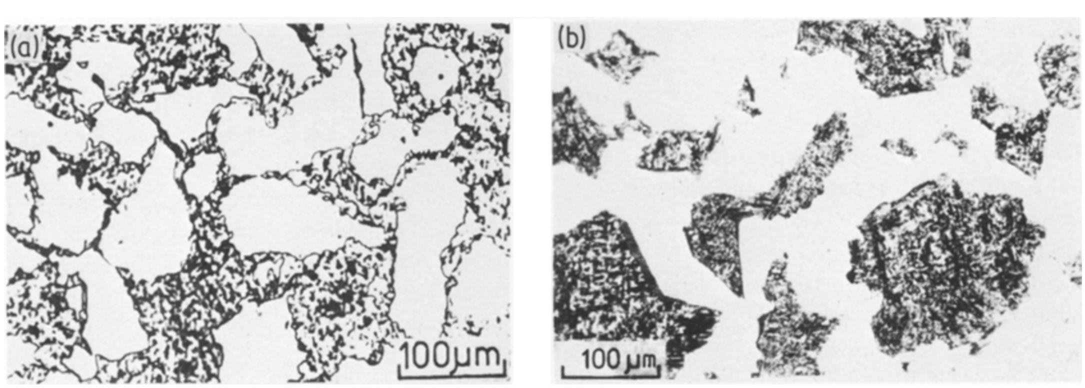

Figure 2 Microstructure of (a) material R and (b) material K.

*The connectivity of the martensitic structure is defined by the parameter ō, where ō = Sl/(Sl + Ml) and Sl is the average number of intersections made with the boundaries of the martensitic structure per unit length (mm^{-1}) and Ml is the average number of intersections with the grain boundaries of the ferrite per unit length (excluding the length shared by the martensitic structure, in mm^{-2}).

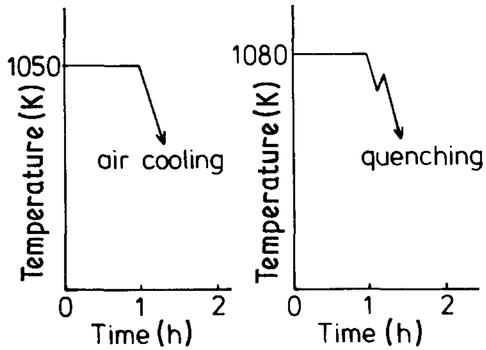

Figure 3 Heat treatment process for material R.

$$\Delta K = \Delta\sigma(\pi\sigma)^{1/2}F(a/w) \quad (1)$$

where

$$F(a/W) = \left(\frac{2w}{\pi a}\tan\frac{\pi a}{2w}\right)^{1/2} \times \frac{0.72 + 2.02(a/w) + 0.37\,[1 - \sin(\pi a/2w)]^3}{\cos(\pi a/2w)} \quad (2)$$

a is the crack length and w is the width of the test-piece.

It is expected in the next section, in the case of crack propagation by ductile cracking caused by accumulating strains, crack propagation is not always accelerated. On the contrary, in the case of R material which readily undergoes static fracture, the microfracture mode will be the static mode.

3. Experimental results and discussion

3.1. Influence of mean stress on crack propagation

It is reported by Paris and Erdogan [2] that the relationship between da/dN and ΔK is not always expressed by $da/dN = C(\Delta K)^m$, because the fracture mechanism depends on the microstructure and ΔK level. Also, it is said that the changes in the m value and the percentage of fracture are caused by different fracture mechanisms which are very important in crack propagation [9]. The purpose of this study is to reveal the dependency of crack propagation on the mean stress in the R and K materials.

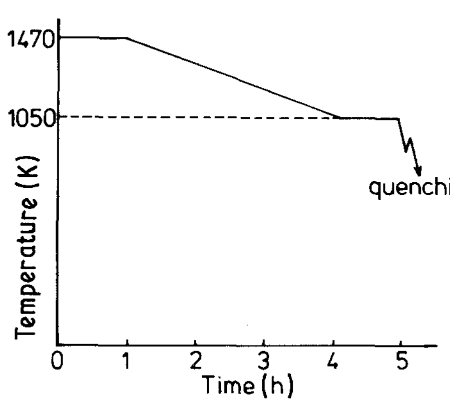

Figure 4 Heat treatment process for material K.

The microstructure of the R material is shown in Fig. 2a and it is expected to undergo cleavage facet fracture from the beginning because most of the microfracture surfaces will be in the static mode, and even if the mean stress is changed, the fracture mode will not transfer from the static mode to a different mode. In contrast, the microstructure of the K material shown in Fig. 2b does not exhibit a static mode from the beginning and its fracture mode changes gradually from slipping to static according to the mean stress level, and since this structure does not consist of martensite networks its dependency on mean stress is remarkable. It may be that the change in mode occurs due to changes in mean stress.

The stress range ($\Delta\sigma$) was set constant and the mean stresses (σ_m) were 26, 53 and 79 MPa. From the crack propagation curve, as shown in Fig. 5,

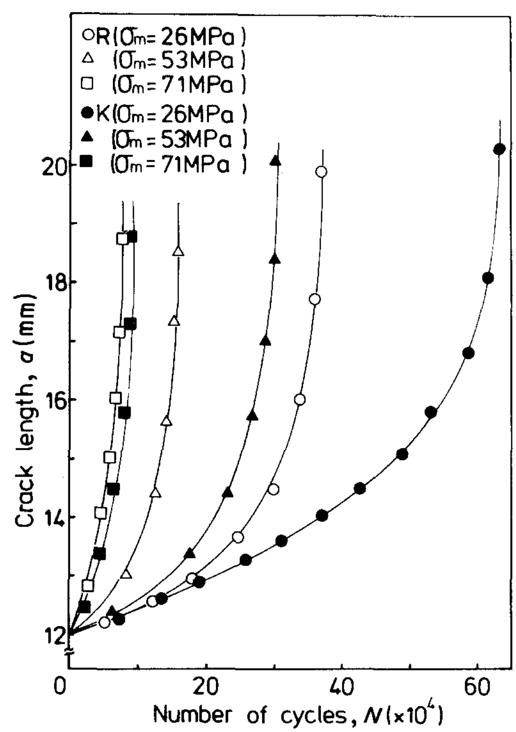

Figure 5 Relationship between crack length and number of cycles.

it was possible to obtain the relationships of da/dN against ΔK, as shown in Figs. 6, 7 and 8.

Figs. 6, 7 and 8 show that the rate of crack propagation in the R material is higher than that in the K material. Figs. 9 and 10 show the individual crack propagation curves for the R and K material, respectively. At a glance each curve seems to be a little different. However, if Fig. 9 is compared with Fig. 10, the differences in the crack propagation rate with mean stress ($\sigma_m = 26$, 53 and 79 MPa) of the R material are small, whereas those of the K material are remarkably different, and the crack propagation rate increases with the increase in mean stress. Fig. 11 shows the crack propagation curves of the R and K materials together.

It is widely known that investigation of the dependence of microfracture mechanisms on the stress intensity factor (ΔK) is useful in research into factors influencing fatigue crack propagation. Striations, cleavage facets, quasi-facets and dimples are observed on the fracture surface. Figs. 12 to 17 show plots of the fracture surface (%) of various fracture modes against ΔK for different mean stresses in the R and K materials.

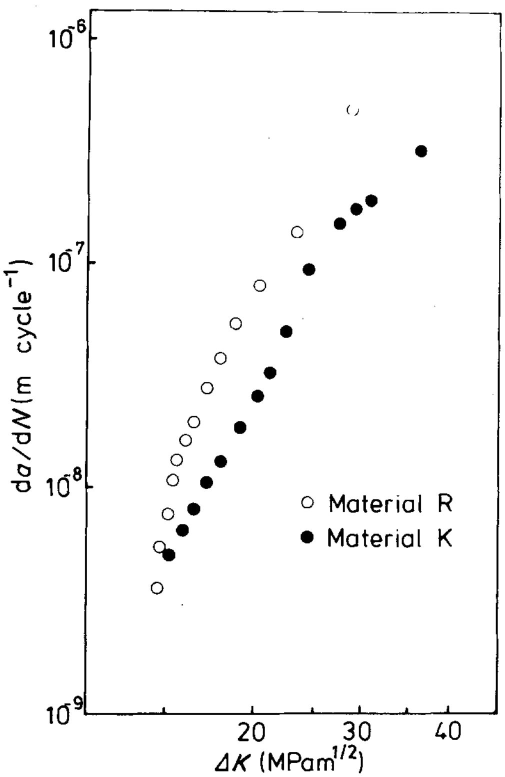

Figure 6 Relationship between crack propagation speed and stress intensity factor at a mean stress of 26 MPa.

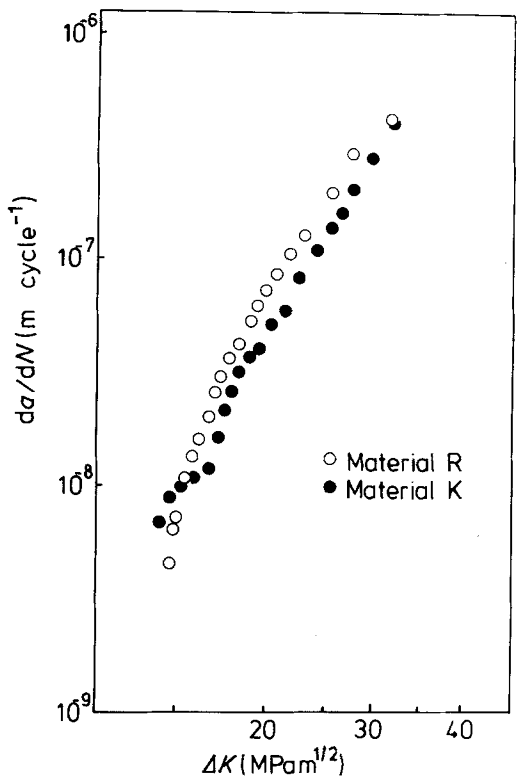

Figure 7 Relationship between crack propagation speed and stress intensity factor at a mean stress of 53 MPa.

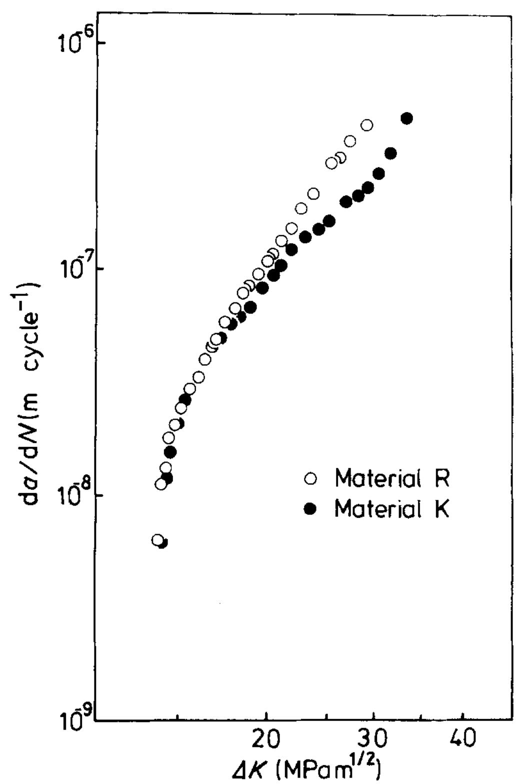

Figure 8 Relationship between crack propagation speed and stress intensity factor at a mean stress of 79 MPa.

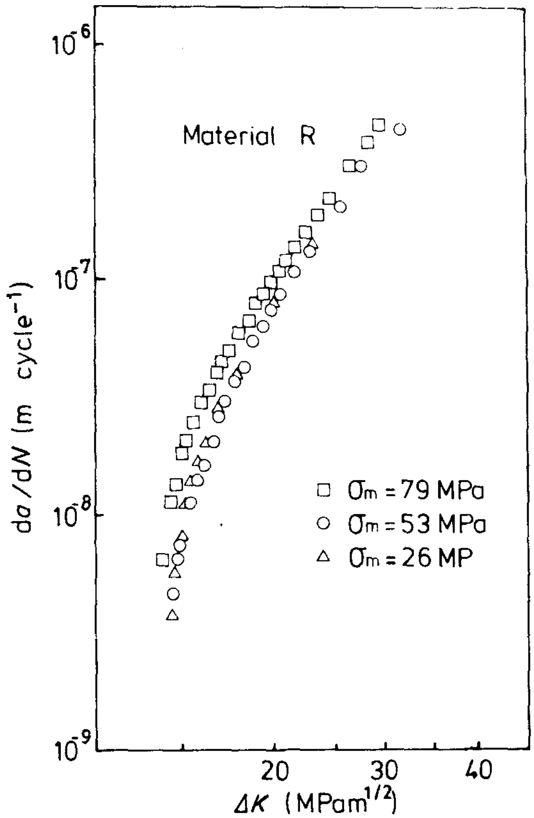

Figure 9 Relationship between crack propagation speed and stress intensity factor for three values of σ_m for the R material.

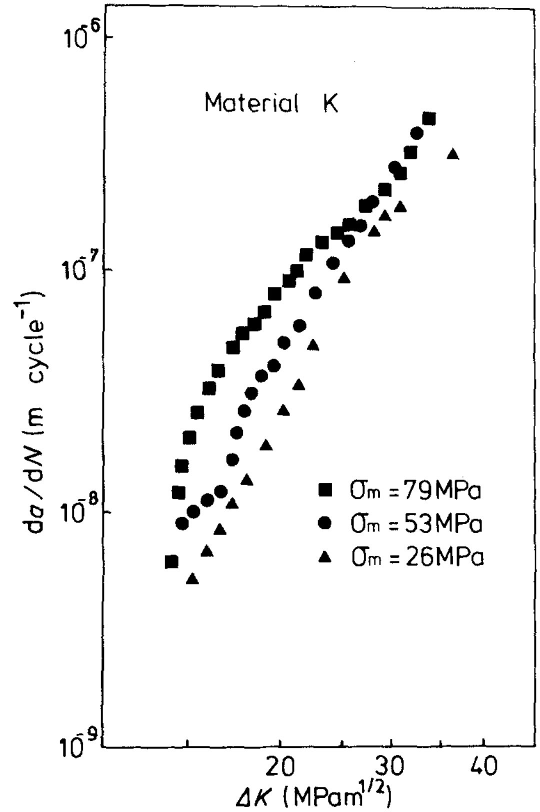

Figure 10 Relationship between crack propagation speed and stress intensity factor for three values of σ_m for the K material.

Now I would like to investigate, using Figs. 12 to 17, the reason why the differences in crack propagation rate occur only in the K material. Each fracture surface percentage depends on the value of ΔK of the R material. If we look closely, the fracture surface percentages of striation in the R and K materials are in inverse ratio to their stress intensity factors. In contrast, fracture surface percentage of dimples, cleavage facets and quasi-cleavage facets increase with increasing ΔK. The changes in the fracture surface percentage of the K material corresponding to Figs. 6 and 8 were investigated. In the case of $\sigma_m = 26$ MPa, the fracture surfaces of cleavage facets, quasi-cleavage facets and dimples, in the region $\Delta K < 20$ MPa were not observed, so that the crack propagation at this stage is the 2b stage consisting of striations. The 2b stage denotes the region of crack growth which is made by striations only, and the distance of striations gives the crack propagation speed. The 2c stage denotes the region of almost final fracture in which static fracture modes or almost the same fracture modes occur. These mechanisms consist of dimples, cleavage facets and intergranular cracks etc., and fatigue crack propagation is influenced by these fracture modes. But in the case of $\sigma_m = 79$ MPa the change from the 2b stage to the 2c stage, depending on the increase in σ_m, occurs at a lower ΔK level. That is to say, it changes from a slipping fracture mode to a static mode depending on the increase in σ_m. The change from a 2b to a 2c stage, depending on σ_m, causes acceleration of crack propagation, and it effects the crack propagation rate dependence on σ_m of the K material. The crack propagation in R material is rapid, even when σ_m is small, and the fracture shows a static fracture mode mainly consisting of dimples and cleavage etc. This phenomenon continues with increasing σ_m. The reason why there is almost no difference in crack propagation between each different σ_m in the R material is that the static fracture mode occurs from a lower σ_m level to a rather higher level.

From these facts, we can see that the influence of σ_m depending on the microstructures for fatigue crack propagation in the R material, and in

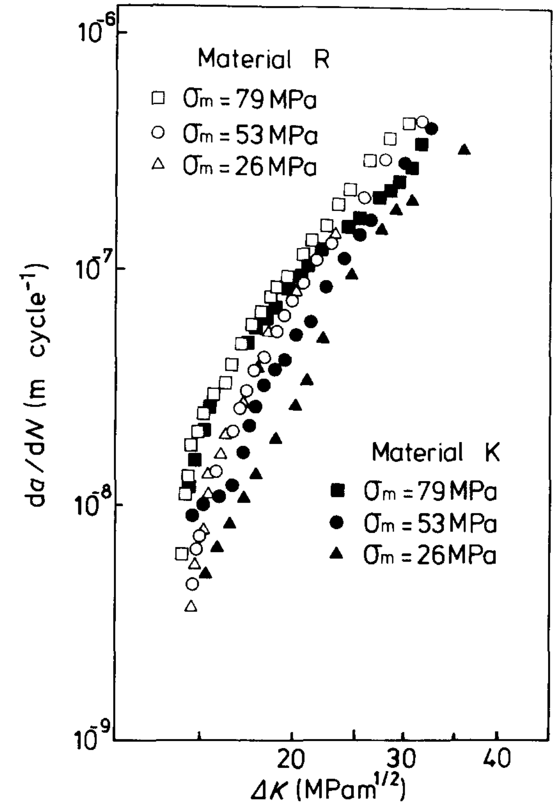

Figure 11 Relationship between crack propagation speed and stress intensity factor for three values of σ_m for both the R and K material.

the K material fatigue crack propagation depends on σ_m. This investigation was carried out from a microstructural point of view.

3.2. Main acceleration factor for crack propagation

All crack propagation rates in the R material exceed those in the K material for values of mean stress equal to 26, 53 and 79 MPa, as shown in Figs. 6, 7 and 8.

It is well known that fatigue crack propagation is accelerated by static fracture modes. It will be interesting to investigate which is the most effective factor in acceleration of crack propagation by cleavage facets, dimples etc.

For this purpose, the difference in fracture percentages for the same values of stress intensity factor in the R and K materials is determined from the x-axis coordinate, and the difference in crack propagation rates from the y-axis coordinate, by using the fractography results, as shown in Figs. 12 to 17. No relationship could be found between the difference in dimple fracture percentages and the difference in crack propagation rates, as shown in Fig. 18. Fig. 19 shows a plot of the difference in cleavage fracture surface percentages against difference in crack propagation rates. It becomes clear that the difference in percentage of cleavage facets accelerates crack propagation depending on the mean stress. This tendency is more remarkable at high values of mean stress.

Also examined was the form of ferrite cleavage facets in the R and K materials, and their microfracture behaviour. It is important to know the parts that the ferrite cleavage facets play in the acceleration of crack propagation by the nature of the microfracture behaviour. For this purpose, each microfracture surface was examined in detail to investigate the dependency of fracture surface on the crack propagation rate by the nature of the ferrite cleavage facet behaviour. As a result, cleavage facets are observed on the fracture sur-

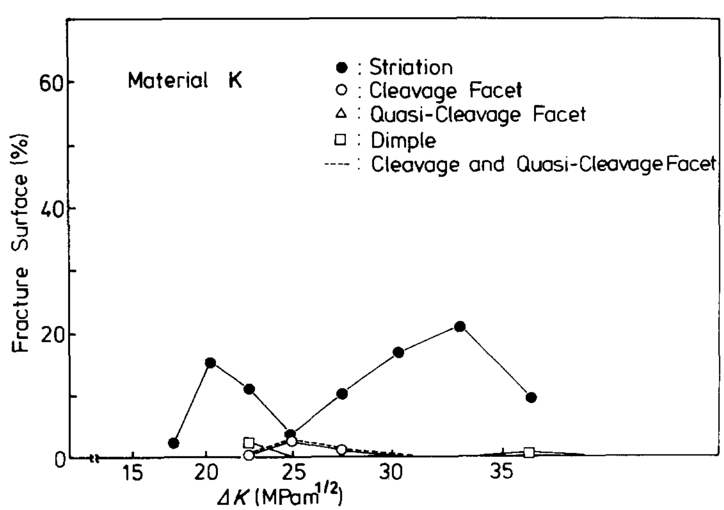

Figure 12 Relationship between fracture surface and stress intensity factor for the K material at a mean stress of 26 MPa.

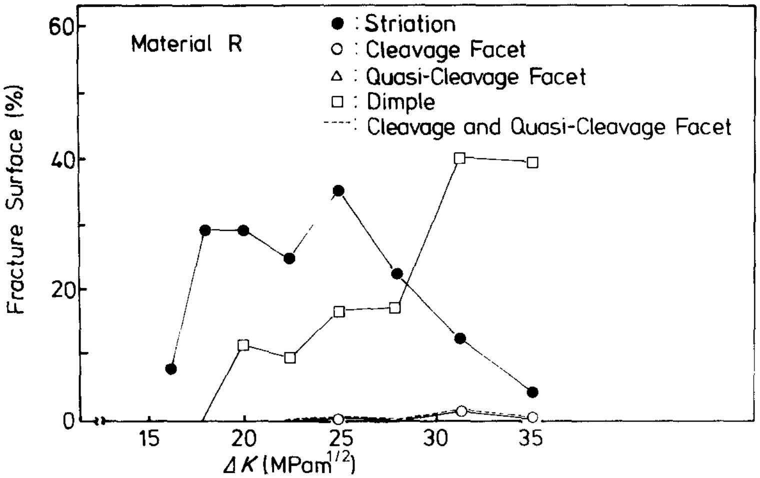

Figure 13 Relationship between fracture surface and stress intensity factor for the R material at a mean stress of 26 MPa.

faces of the R and K materials, as shown in Fig. 20. From these observations, it became clear that cleavage facets in the R material occur continuously in the neighbouring ferrite grains, as shown in Fig. 20a, whereas those in the K material occur in isolation in the microstructures, as shown in Fig. 20b. From the increase in the number of continuous cleavage facets in the R material, as shown in Fig. 21, which has the largest difference in crack propagation rates (see Fig. 6 etc.), the number of cleavage facets shows a tendency to depend on the acceleration of the crack propagation. At the highest value of mean stress, 79 MPa, the number of continuous cleavage facets in the high stress intensity range increases greatly (see Fig. 22). This exhibits some dependence on the differences in the R and K materials. In contrast, few continuous and isolated cleavage facets occur in the K material at mean stresses of 79 and 26 MPa, as shown in Figs. 21 to 24. The number of isolated cleavage facets in the R material is too small to accelerate fatigue crack propagation. For this reason, the

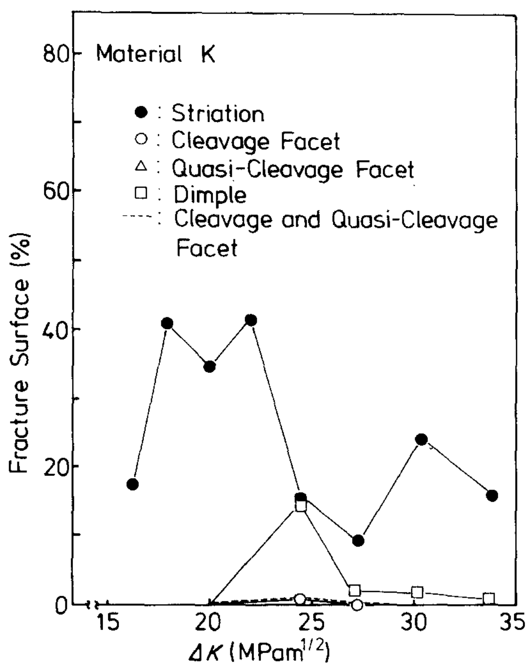

Figure 14 Relationship between fracture surface and stress intensity factor for the K material at a mean stress of 53 MPa.

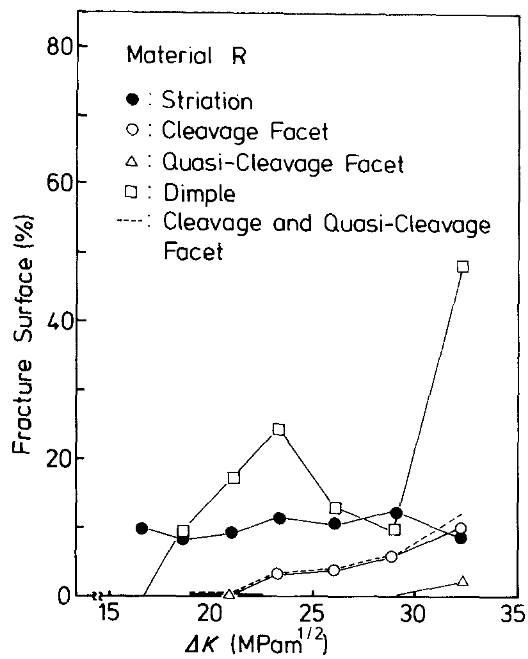

Figure 15 Relationship between fracture surface and stress intensity factor for the R material at a mean stress of 53 MPa.

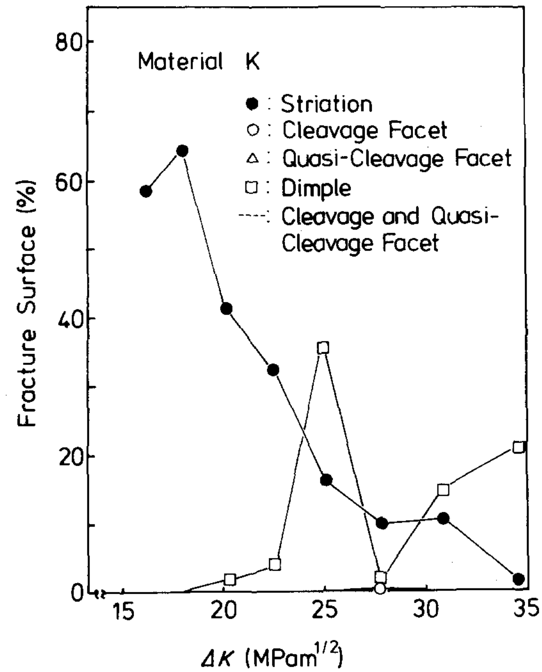

Figure 16 Relationship between fracture surface and stress intensity factor for the K material at a mean stress of 79 MPa.

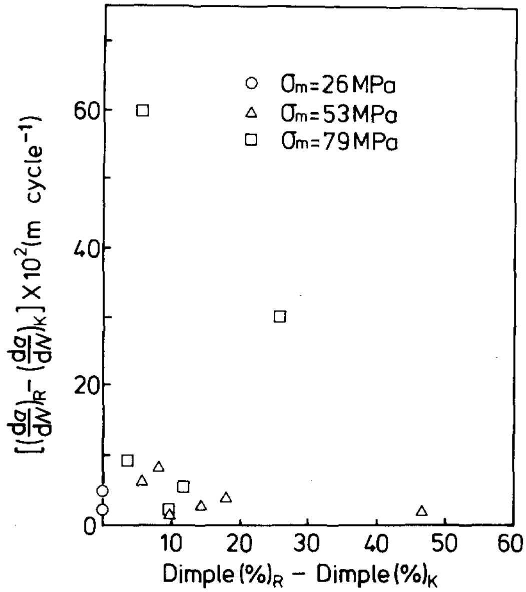

Figure 18 Relationship between the difference in crack propagation speed between the R and K materials and their percentage difference in dimple fracture surface.

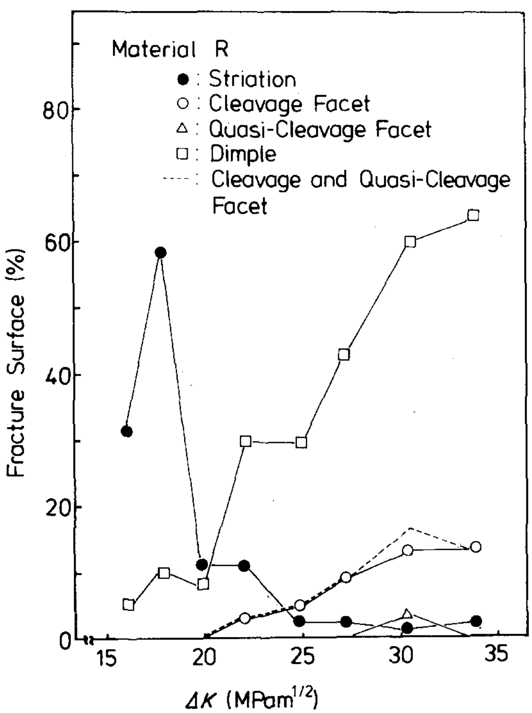

Figure 17 Relationship between fracture surface and stress intensity factor for the R material at a mean stress of 79 MPa.

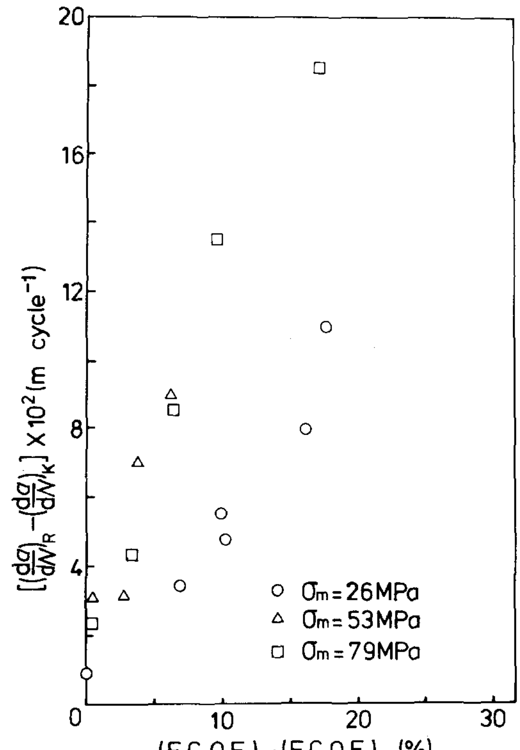

Figure 19 Relationship between the difference in crack propagation speed between the R and K materials and their percentage difference in cleavage surface.

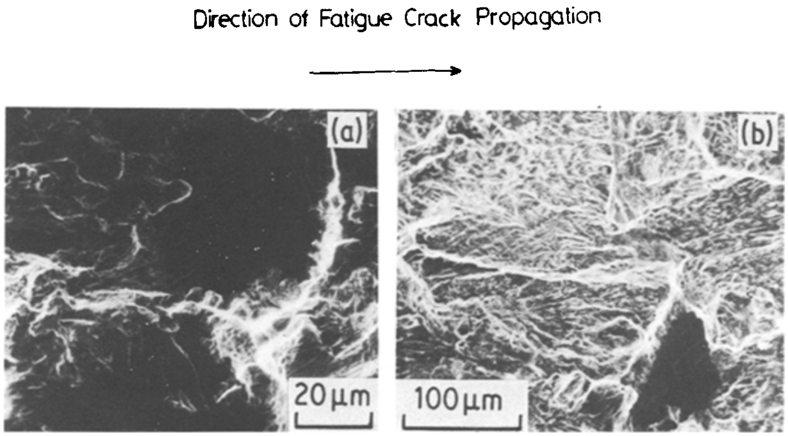

Figure 20 Cleavage facet appearance in (a) R material and (b) K material.

influence of dual-phase microstructures on crack propagation becomes clear, namely, by the difference in the microstructural form of the fracture surfaces.

4. Conclusions

1. In the case of a material in which cleavage facet fracture does not easily occur at its crack tip, fatigue crack propagation depends on mean stress, and its rate accelerates depending on the change from the slipping fracture mode to the static mode.

2. In the case of a material in which cleavage facet fracture easily occurs, the crack propagation depends on the static fracture mode from the beginning, and the change in propagation rate, which depends on mean stress, is small because the change in the microfracture mode is very small.

3. The main factor in accelerating fatigue crack propagation depends on the number of continuous cleavage factes which occur at adjoining matrix grains.

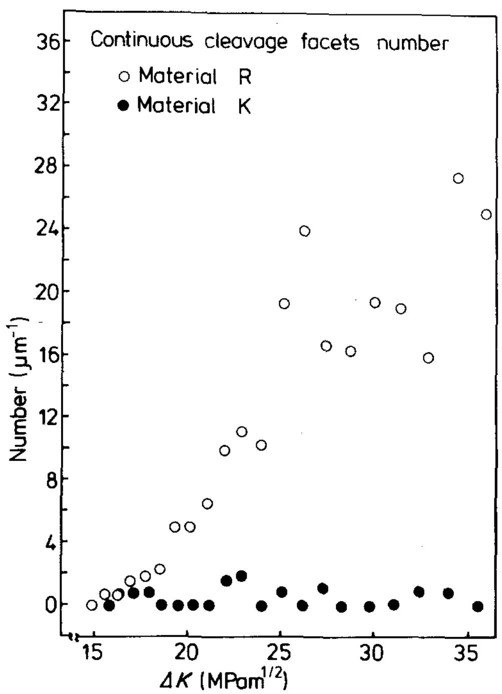

Figure 21 Relationship between continuous cleavage facet number and stress intensity factor at a mean stress of 26 MPa.

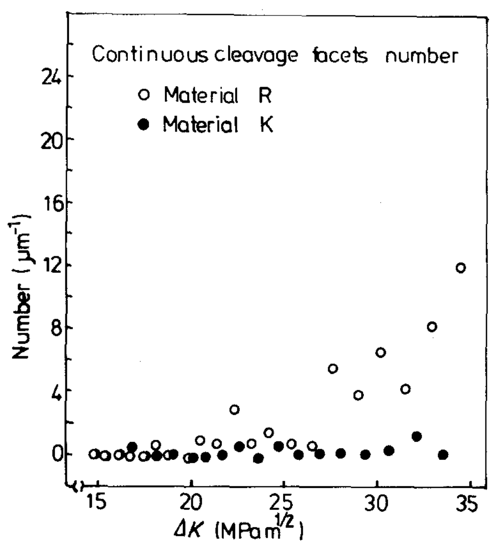

Figure 22 Relationship between continuous cleavage facet number and stress intensity factor at a mean stress of 79 MPa.

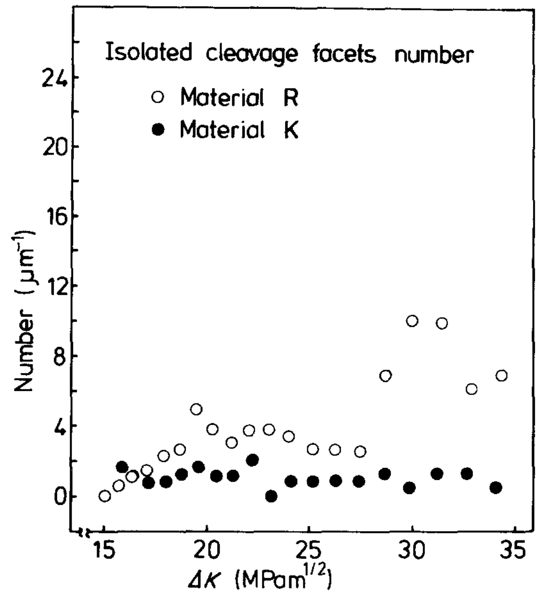

Figure 23 Relationship between isolated cleavage facet number and stress intensity factor at a mean stress of 26 MPa.

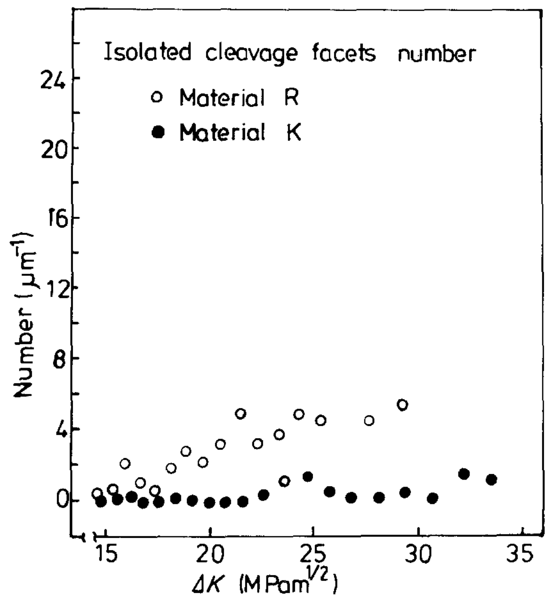

Figure 24 Relationship between isolated cleavage facet number and stress intensity factor at a mean stress of 79 MPa.

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