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The Growth Behaviour of Microstructurally Small Fatigue Cracks in Metals

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ABSTRACT Small fatigue cracks whose growth rates are markedly affected by microstructural features are termed microstructurally small cracks (MSSC). Thus, MSSC show a complicated growth behaviour depending on the microstructure of the material. In the present paper, recent experimental results are surveyed on the growth of MSSC in a wide range of metals. It is shown that crack growth rates often decrease at grain boundaries, triple points, phase interfaces and also decrease due to crack deflections below a certain size which depends on a given material microstructure. The growth behaviour of MSSC is discussed in terms of microstructural effects, the correlation between MSSC and a stage I crack, and the MSSC to LEFM-controlled crack transition.

Introduction

Small fatigue cracks are divided into three categories based on experimental observations, i.e., microstructurally small cracks (MSSC), mechanically small cracks, and small cracks regarded as large cracks (physically small cracks), as shown in Fig. 1 **(1)(2)**.

Physically small cracks are simply small in size and show the same growth behaviour as large cracks when linear elastic fracture mechanics (LEFM) is applied to characterize their growth rates. Mechanically small cracks grow faster than large cracks due to the reduction in crack closure. In some cases, although small-scale yielding (SSY) condition may not be met, the deviation from SSY condition only affects crack closure behaviour. This has been confirmed experimentally by crack closure measurements **(2)–(4)**. Thus, the LEFM parameter, ΔK_{eff}, can be used to correlate growth rates with those of large cracks.

On the other hand, the growth behaviour of MSSC is much more complicated because of the impact of microstructural artefacts. In general, the size of MSSC is almost the order of, or a few times of, microstructural unit size; thus LEFM is not applicable because of continuum mechanics limitations.

In order to characterize the growth rates of MSSC, micromechanics and statistical approaches have recently been developed **(5)–(11)**. However, it seems that they do not always succeed possibly because of insufficient experimental results. In modelling and improving such models, the most important point is to incorporate experimental findings from detailed observations. To this

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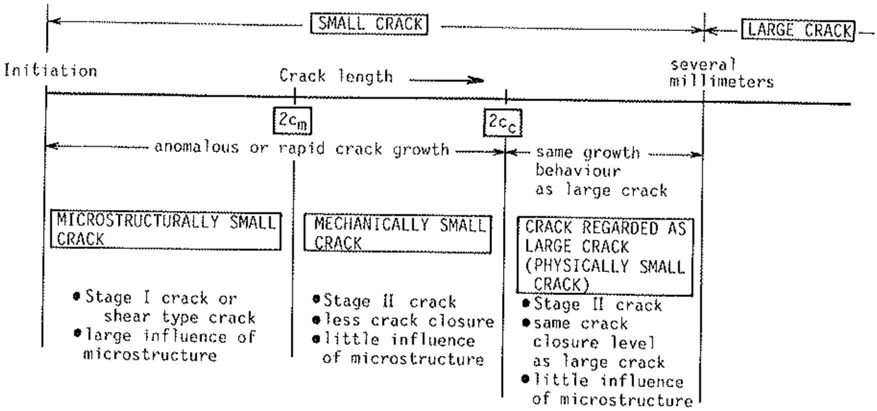


Fig 1 **Three regimes of small fatigue cracks and their corresponding mechanisms and characteristics**

end, it is useful to review the growth behaviour of MSSC over a wide range of materials.

In this paper, recent experimental results are surveyed on the growth of MSSC in seven different metals **(1)(4)(12)–(16)**. The growth behaviour of MSSC is discussed in terms of the microstructural effects, the correlation between MSSC and stage I cracks, and the MSSC to LEFM-controlled crack transition.

Materials

Although there has been considerable work on the growth of small fatigue cracks, studies which have been reported by the authors were chosen for the purpose of the present study because the growth behaviour of MSSC is observed in more detail over a wide range of metals having different well-defined microstructures, microstructural unit sizes, and strengths.

Studies are referenced in Table 1. Also included are various, loading types (RB: rotating bending, AX: axial loading), stress ratio (R), microstructural unit size (d), yield stress (σ_y), fatigue limit ($\sigma_{\max,\,w}$), and the maximum size of MSSC ($2c_m$). The materials cover seven metals: low carbon steel (S10C) **(13)**, medium carbon steel (S45C) **(14)**, high tensile steel (HT60) **(1)**, low alloy steel (SCM435) **(12)**, dual-phase stainless steel (SUS329J1) **(4)**, aluminum alloy (7075-T6) **(15)**, and pure titanium (TB35C) **(16)**. Microstructural unit size (d) is considered to be the approximate martensite packet size for SCM435, the mean pearlite spacing for S45C, and the mean ferrite spacing for SUS329J1, while for other metals it is the average grain size. For 7075-T6 which has a pancake microstructure, the average grain size in the normal direction was employed as microstructural unit size because grain boundaries in that direction strongly affected surface crack growth rate, as will be shown later.

Table 1 Material, test conditions, and microstructural parameters

Materials	*Loading type*	R	d (μm)	σ_y (MPa)	$\sigma_{max,w}$ (MPa)	$2c_m$ (μm)
Low carbon steel (S10C) **(13)**	RB	-1	24/84	286/233	220/190	200/250
Medium carbon steel (S45C) **(14)**	RB	-1	14	296	215	440
High tensile steel (HT60) **(1)**	RB	-1	10	521	340	100
Low alloy steel (SCM435) **(12)**	RB	-1	5/40	847/900	500/460	45/273
Dual-phase stainless steel (SUS329J1) **(4)**	AX	$0/-1$	100	640	560/370	0/100
Aluminum alloy (7075-T6) **(15)**	AX	$0/-1/-2$	14	543	290/190/150	0/95/150
Pure titanium (TB35C) **(16)**	RB	-1	73/115	324/246	240/220	450/690

In all the studies cited, smooth specimens were used to examine the growth behaviour of MSSC, thus cracks were naturally initiated and grown.

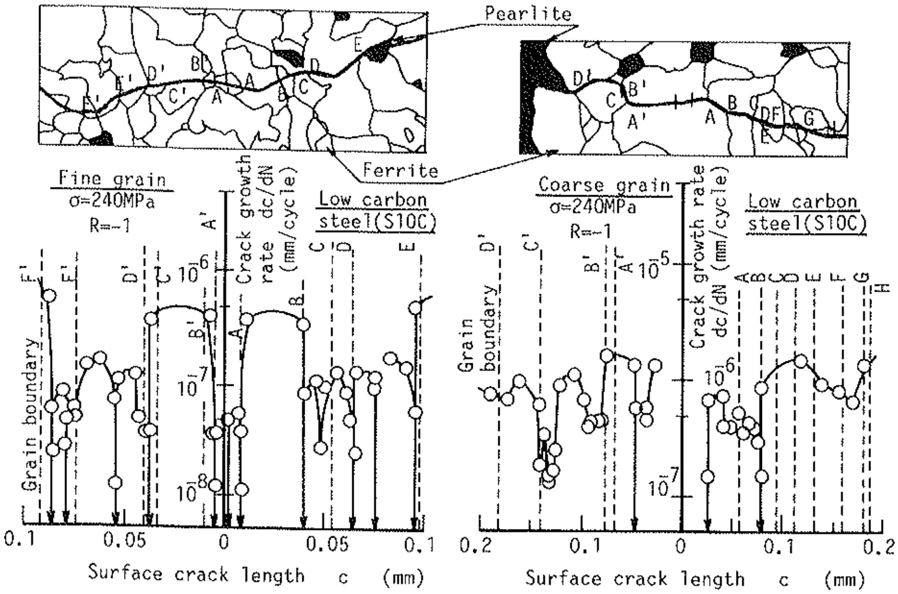
Growth behaviour of microstructurally small cracks

The growth of MSSC has been examined in more detail using a unique replication technique which was first adopted by the authors **(12)**. The results obtained are represented as the relationship between surface crack growth rate (dc/dN) and half surface crack length (c).

The growth behaviour of MSSC in S10C is shown in Fig. 2 **(13)**. Arrows in this figure indicate that the crack tips were held up at an obstacle over many cycles, thus giving a growth rate too low to be plotted within the axes. As can immediately be seen from the figures, in both fine and coarse grained materials, crack growth rates clearly decrease at ferrite grain boundaries and triple points of grain boundary. It is also found that large decreases in crack growth rate indicated by arrows are more pronounced in fine grained material than in coarse grained material. The effect of grain boundaries completely disappears at a crack length of approximately 200 μm and 250 μm for fine and coarse grained materials respectively, and above these crack lengths crack growth rates increase monotonically with increasing crack length.

Similar decreases in crack growth rate at ferrite grain boundaries were also observed in HT60 in the region of crack length below 100 μm **(1)**.

In quenched and tempered steel, SCM435, prior austenite grain boundaries act as barriers to the growth of MSSC. Such examples are demonstrated for fine and coarse grained materials in Fig. 3 **(12)**, clearly showing that crack growth rates are decreased by prior austenite grain boundaries. Austenite grains contain several martensite packets. Therefore, it is considered that the boundaries between martensite packets also act as barriers as well as austenite grain boundaries. Large decreases in crack growth rate at positions other than

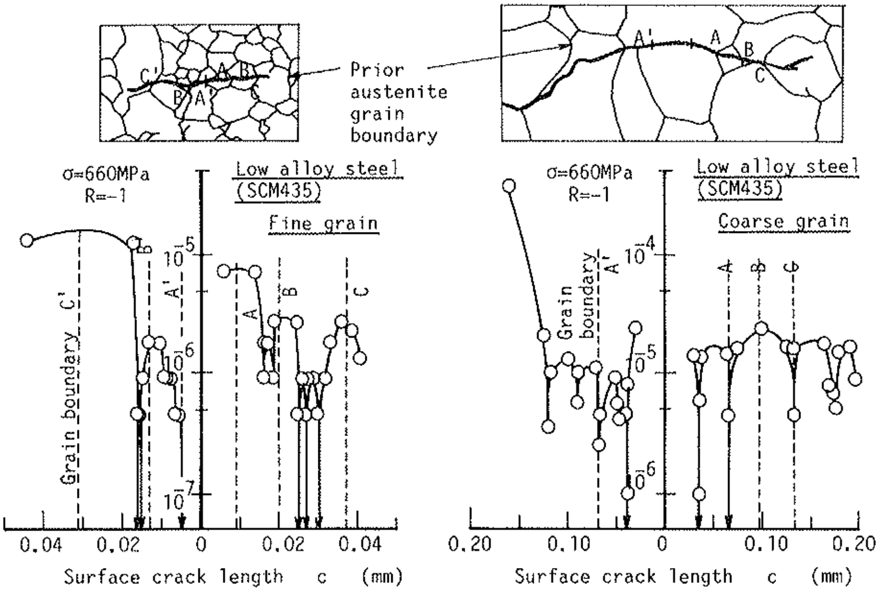


(a) Fine grain (b) Coarse grain

Fig 2 **Growth behaviour of microstructurally small cracks for fine and coarse grained materials in low carbon steel (S10C)**

austenite grain boundaries may be due to such boundaries. In addition, the effect of grain size on the growth of MSSC is the same as that in S10C, i.e., less frequent large decreases in crack growth rate in coarse grained material. In this steel, the effect of microstructure disappears at a crack length of approximately 45 μm and 273 μm for fine and coarse grained materials, respectively.

The microstructures of S45C and SUS329J1 consist of two phases: ferrite and pearlite in the former and ferrite and austenite in the latter. In these materials, when cracks grow into a stronger and harder phase from a weaker and softer one, boundaries between two phases tend to impede their growth. For example, it has been indicated that in dual-phase steels with ferrite and martensite phases, crack growth rates and crack path were strongly affected by martensite phase, even in large crack growth **(17)–(19)**. Moreover, steels with ferrite and pearlite phases have been examined by de los Rios *et al.* **(5)(20)** who showed that cracks were held up by the interfaces between two phases, sometimes ceasing growth entirely on reaching these boundaries. Similar results obtained in S45C **(14)** and SUS329J1 **(4)** are represented in Fig. 4. As cracks grow into pearlite phase from ferrite phase in S45C and austenite phase from ferrite phase in SUS329J1, it is clear that crack growth rates show a marked decrease at phase interfaces. Furthermore, it is also observed that cracks tend to grow predominantly within ferrite phase in S45C.



(a) Fine grain

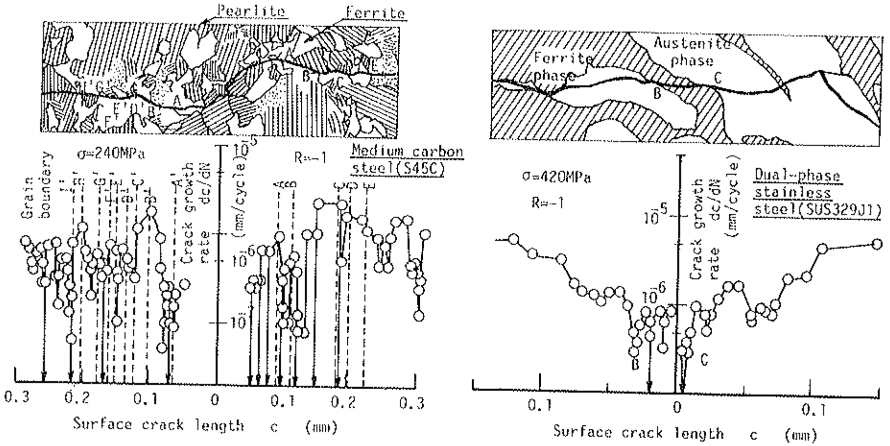
(b) Coarse grain

Fig 3 **Growth behaviour of microstructurally small cracks for fine and coarse grained materials in low alloy steel (SCM435)**

As can be seen from Figs 2–4, crack growth rates also decrease at positions other than grain boundaries and boundaries between phases. There are two possible explanations for this behaviour: as crack growth rates decrease, crack front reaches these interior boundaries **(12)** and small crack deflections take place.

The effect of microstructure on crack growth rate has also been obtained in metals other than steels. Figure 5 shows the growth behaviour of MSSC at two different stress ratios of 0 and −1 in aluminum alloy 7075-T6 **(15)**. It is found that at $R = 0$ cracks which initiated at inclusions indicate no significant effect of microstructure (Fig. 5(a)), while at $R = -1$ crack growth rates decrease at a grain boundary (Fig. 5(b)). Thus, the growth of MSSC depends strongly on stress ratio.

For fine and coarse grained materials in pure titanium, the growth behaviour of MSSC has been examined in detail on each of ten specimens at a given stress level. The results are illustrated in Fig. 6 **(16)**. In this material, the crack path was extremely tortuous as shown in Fig. 7, being more remarkable with increasing grain size, thus the decreases in crack growth rate result from two causes: grain boundary and crack deflection. As can be seen from Fig. 6, large decreases in crack growth rate are observed more frequently in fine grained material as compared to coarse grained material, similar to the results in S10C



(a) Medium carbon steel(S45C)

(b) Dual-phase stainless steel(SUS329J1)

Fig 4 Growth behaviour of microstructurally small cracks in metals with composite microstructures

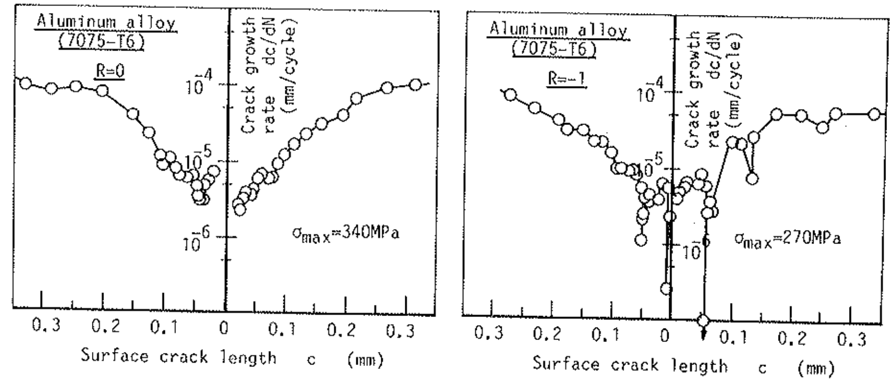
(Fig. 2) and SCM435 (Fig. 3), while the variation in crack growth rate extends to larger crack length in the latter material.

Discussion

Microstructural effects

Microstructure

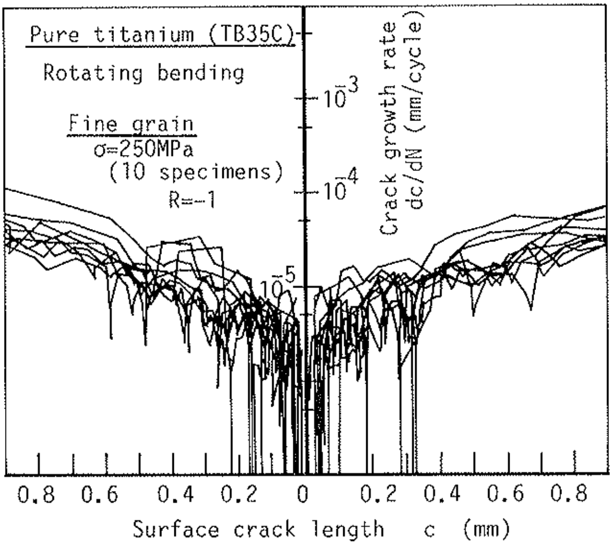
The materials chosen in the present study cover different crystal structures, such as BCC (S10C, S45C, HT60 and SCM435), FCC (7075-T6), HCP (TB35C) and BCC-FCC (SUS329J1) structures. Therefore, it is interesting to



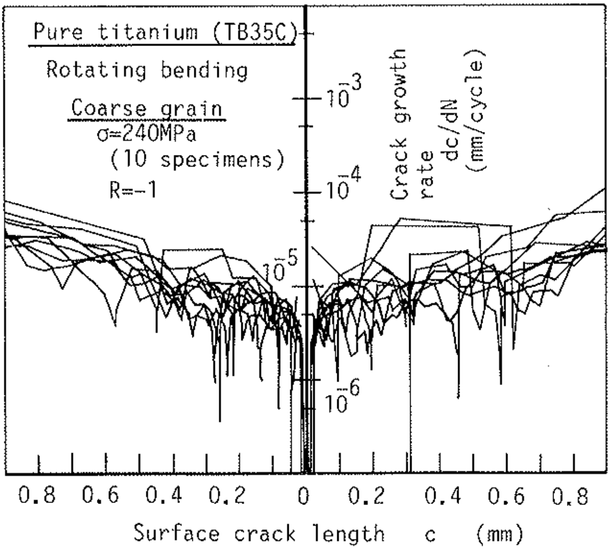
(a) Stress ratio R=0

(b) Stress ratio R=−1

Fig 5 Growth behaviour of microstructurally small cracks at two stress ratios in aluminum alloy (7075-T6)



(a) Fine grain



(b) Coarse grain

Fig 6 **Growth behaviour of microstructurally small cracks for fine and coarse grained materials in pure titanium (TB35C). Data are obtained on each of ten specimens used at a given stress level**

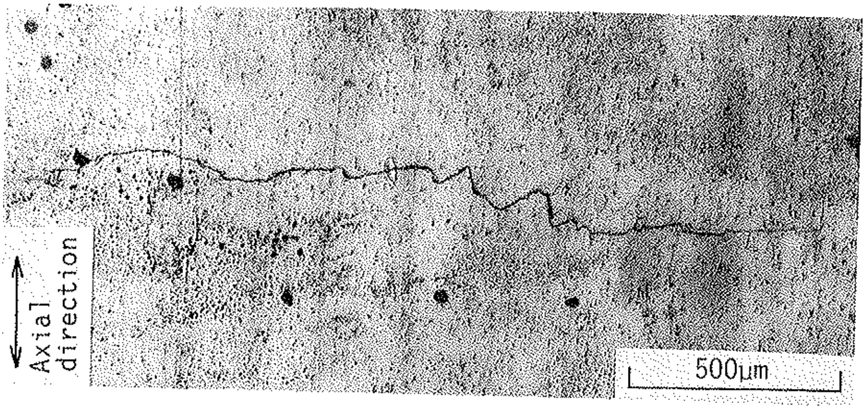


Fig 7 Macroscopic crack growth appearance for fine grained material of pure titanium, showing that crack path is severely deflected

compare the growth behaviour of MSSC among these metals. Although a direct comparison is not easy because of the differences in test conditions (stress level, loading type, etc.), as can be seen from Figs 2–6, the overall behaviour of MSSC is similar in all the metals; crack growth rates often temporarily decrease at grain boundaries, triple points and boundaries between two phases. The blocking effect of grain boundaries is considered to result from the misorientation between the grain containing a crack and the adjacent grain. However, the crystallographic condition between two grains by which crack growth rates are decreased has not been clarified. A crystallographic study on 3%Si iron using an etch pit technique is in progress by the authors.

The growth behaviour of MSSC in pure titanium is somewhat different from that of other metals. As mentioned above, in general, the crack path experiences severe deflections which are responsible for the decrease in crack growth rate in addition to the effect of grain boundaries, because the deflected crack path tends to lower the crack driving force as described by Suresh **(21)**. The tortuous nature of crack path morphology in this metal may be associated with planar slip characteristic or fewer slip systems than bcc and fcc metals, i.e., as cracks reach grain boundary, large changes of growth direction would occur due to the incompatibility of deformation (i.e., misorientation) between two grains.

Grain size

Much of the published work on the effect of grain size on small fatigue crack growth indicates that increasing grain size leads to faster crack growth rates **(22)–(24)**. In the region of MSSC, this trend in the grain size effect would be due to the difference in the blocking effect of grain boundaries. As can be clearly seen from Figs 2, 3, and 6, the blocking effect of grain boundaries is more frequent in fine grained material than in coarse grained material. Thus, one can expect that this leads to decreased average crack growth rates and contributes greatly to an increased overall fatigue life in fine grained material.

The effect of grain size can be seen more clearly in pure titanium (Fig. 6). The crack growth rates at a given crack size followed log-normal distributions independent of grain size **(16)**. The coefficients of variation of crack growth rate obtained are represented for fine and coarse grained materials in Fig. 8 as a function of normalized crack depth (*a*/*d*) (*a*: crack depth). The scatter of crack growth rates is considerably larger in the region of $a/d < 3$ independent of grain size, thus this region is considered to correspond to the growth of MSSC. Furthermore, the coefficients of variation in coarse grained material are smaller compared to fine grained material, also reflecting that the blocking effect of grain boundaries is less frequent in coarse grained material than in fine grained material, as mentioned previously.

Stress ratio

Although it has been indicated that increasing the stress ratio moved small crack growth rates to lower stress intensities, as large cracks **(23)(25)**, data are limited, in particular at negative stress ratios. As shown in Fig. 5, the microstructural effect is more remarkable at $R = -1$ than at $R = 0$. The result at

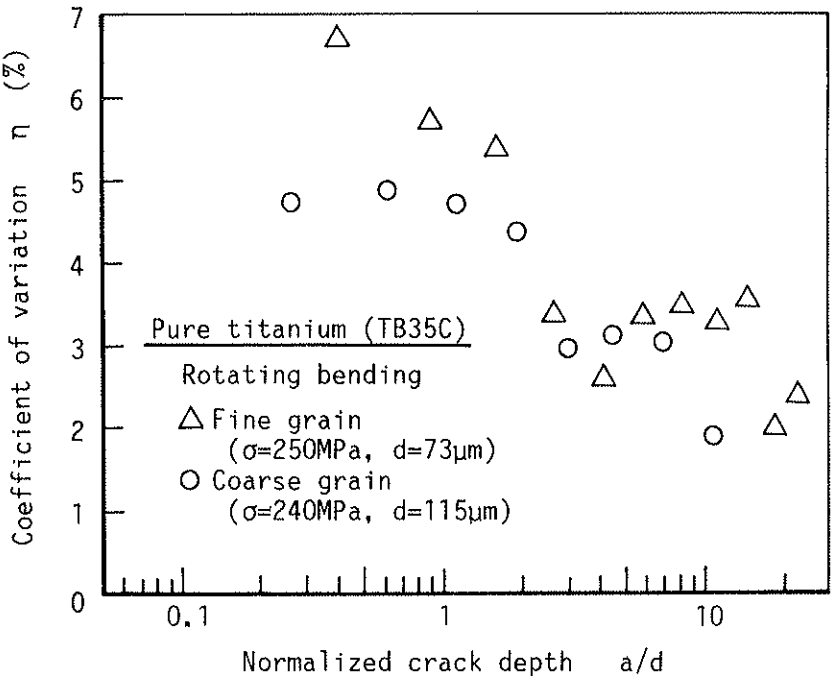


Fig 8 Relationship between coefficient of variation of crack growth rate and normalized crack depth for fine and coarse grained materials in pure titanium (TB35C)

$R = -2$ was also obtained and indicated a clear effect of microstructure (**15**). When crack growth rates at all the stress ratios are characterized by the maximum stress intensity (K_{max}), the results at $R = -2$ showed the fastest crack growth rates followed by the results at $R = -1$ and $R = 0$ in that order of decreasing crack growth rate. Therefore, it is clear that the microstructural effect and crack growth rate are extremely sensitive to stress ratio. As will be discussed later, stage I facets were observed on the fracture surfaces at $R = -1$ and -2, but not at $R = 0$, indicating that the existence of stage I facets is closely related to the growth of MSSC. Similar effects of stress ratio were also obtained in SUS329J1 (**4**).

In summary, the effects of stress ratio suggest that compressive component of the applied load would play an important role in the formation of stage I facets and as crack driving force. Further study is needed to confirm this for other materials.

Microstructurally small crack and stage I crack

In the region where crack growth rates were affected by microstructure, flat and featureless facets have been observed on fracture surface in almost all of metals except for SUS329J1. The examples of such facets are shown for S10C, 7075-T6 and TB35C in Fig. 9.

Many parallel straight lines are recognized on the facets in S10C (Fig. 9(a)), and the direction of these straight lines has been confirmed to be consistent with the slip direction $\langle 111 \rangle$ of this material by the use of etch pits developed on the facets (**14**). This indicates that the straight lines were formed as a result of pencil-glide slip, thus cracks grew along slip planes in a shear mode, i.e., stage I crack growth mechanism.

As mentioned in the previous section, similar facets were observed at $R = -1$ (Fig. 9(b)) and $R = -2$ in 7075-T6, but not at $R = 0$, indicating that the formation of stage I facets is largely affected by stress ratio.

Very clear facets were observed in all the TB35C specimens and an example is shown in Fig. 9(c). The depths of stage I facets (a_I) obtained in fine and coarse grained materials are plotted on a log-normal probability paper, together with grain size, and are represented in Fig. 10. The results show that for both materials the distributions of a_I and grain size follow log-normal distributions. The a_I values are clearly dependent on grain size, and the distributions are localized at the larger size in the distribution of grain size for each material. Moreover, the variances of the distributions of a_I tend to be small compared to those of grain size, in particular in coarse grained material. It is considered, therefore, that the distributions of a_I represent the maximum value distribution of grain size. This means that cracks generate in relatively large grains which meet crystallographic conditions for crack initiation.

From the above observations, MSSC exactly corresponds to stage I cracks except for S45C which has strong barriers of pearlite. Thus, it is rationalized

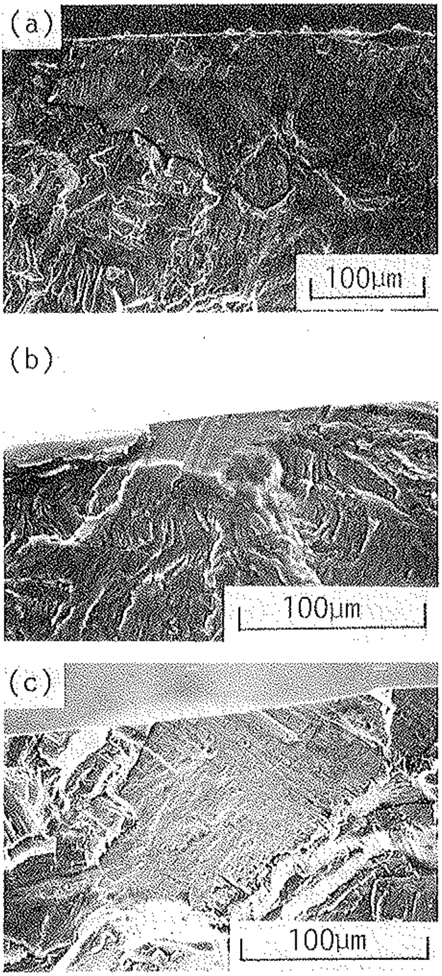


Fig 9 **Examples of stage I facets observed:**
(a) low carbon steel (S10C, coarse grain);
(b) aluminum alloy (7075-T6, $R = -1$);
(c) pure titanium (TB35C, fine grain)

that the microstructural effect occurs as a sequence of stage I crack growth, i.e., crystallographic growth.

Transition from microstructurally small crack to mechanically small crack

The most remarkable difference in the growth of MSSC among metals is the crack length below which crack growth rates are affected by microstructure, i.e., the size of MSSC ($2c_m$). This crack size is also the MSSC to mechanically

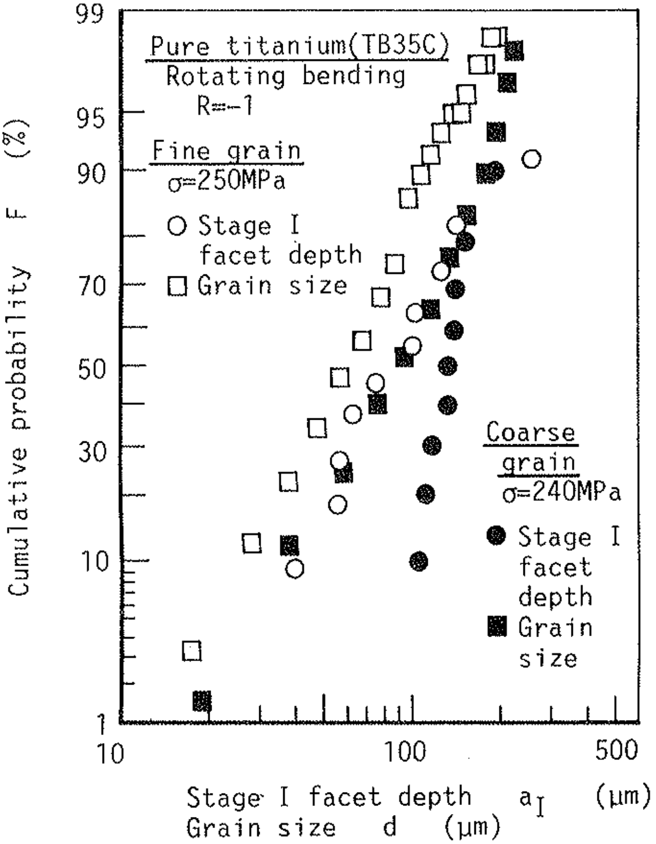


Fig 10 **Distributions of stage I facet depth and grain size for fine and coarse grained materials in pure titanium plotted on a log-normal probability paper**

small crack (ΔK_{eff} control) transition, i.e., stage I to stage II crack transition, as shown in Fig. 1. Values of $2c_{\mathrm{m}}$ are necessary for the application of conventional large crack data to small crack growth as a lower limit of crack length. The maximum values in $2c_{\mathrm{m}}$ obtained from various test conditions are given in Table 1 for all metals considered. The authors have already pointed out that a functional correlation of $2c_{\mathrm{m}} = 9d$ for $d < 30$ μm and $2c_{\mathrm{m}} \sim 260$ μm for $d > 30$ μm for three types of steel **(1)**. In the present study, however, the correlation between both is of the form $2c_{\mathrm{m}} = 8d$ for a wide range of metals as shown in Fig. 11. Taylor and Knott **(26)** and Taylor **(27)** have also suggested that the transition took place at the crack length of $10d$. However, it should be noted that this transition of $10d$ does not mean the MSSC to mechanically small crack transition, but the mechanically small crack to physically small crack (ΔK control) transition, i.e., $2c_{\mathrm{c}}$ defined in Fig. 1.

In Fig. 11, note that the data of the materials with composite microstruc-

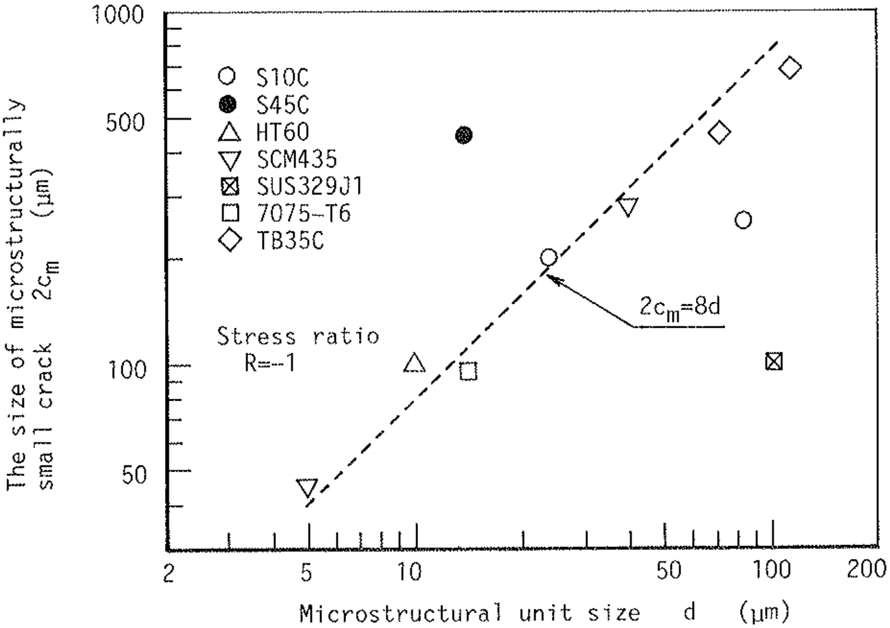


Fig 11 Correlation between the size of microstructurally small cracks and microstructural unit size in a wide range of metals

tures such as S45C and SUS329J1 largely deviate from the correlation of $2c_m = 8d$. One of the reasons may be attributed to the definition of microstructural unit size. In S45C, in addition, the $2c_m$ value becomes larger due to strong barriers of zones than expected from the correlation, also suggesting the continuing microstructural sensitivity even after the transition to stage II.

The correlation of $2c_m = 8d$ obtained is for a stress ratio of -1. However, the $2c_m$ values are affected by stress ratio as indicated in SUS329J1 and 7075-T6 (see Table 1). Thus, further work is needed to establish the correlation between $2c_m$ and d for different stress ratios.

A simulation for the growth of microstructurally small cracks

Based on the experimental findings of the growth behaviour of MSSC, a modelling and computer simulation are in progress. In brief, a Monte Carlo simulation is performed by giving both microstructural and crystallographic parameters as random variables in order to express the growth of MSSC interacting with grains, and crack growth rates are computed as functions of crack length and stress intensity.

The results which are in agreement with the experimental results for pure titanium have been obtained, and will be presented elsewhere.

Conclusions

(1) The overall growth behaviour of microstructurally small cracks (MSSC) is similar in all materials; crack growth rates are markedly decreased by grain boundaries, triple points and interfaces between phases depending on the microstructures. Crack growth rates also decrease due to crack deflections, as clearly seen in pure titanium.

(2) The growth of MSSC is sensitive to grain size, and large decreases in crack growth rate due to microstructure are more frequent in fine grained material than in coarse grained material. This leads to decreased average crack growth rates and contributes greatly to an increased overall fatigue life in the former material.

(3) The microstructural effect is much more remarkable at negative stress ratio, and the existence of stage I facets is strongly related to stress ratio.

(4) The MSSC exactly corresponds to stage I cracks, except for a medium carbon steel with strong barriers of pearlite phase. Thus, it is rationalized that the microstructural effect occurs as a sequence of stage I crack growth, i.e., crystallographic growth.

(5) The crack length at the transition from MSSC to mechanically small crack, (ΔK_{eff} control) can be estimated to be $8d$ for a stress ratio R of -1, d being the microstructural unit size.

References

(1) TOKAJI, K., OGAWA, T., and HARADA, Y. (1987) Evaluation on limitation of linear elastic fracture mechanics for small fatigue crack growth, *Fatigue Fracture Engng Mater. Structures*, **10**, 281–289.

(2) TOKAJI, K., OGAWA, T., OSAKO, S., and HARADA, Y. (1987) The growth behaviour of small fatigue cracks; the effect of microstructure and crack closure, *Fatigue '87*, Vol. 2, pp. 313–322.

(3) TOKAJI, K., OGAWA, T., and AOKI, T. (1990) Small fatigue crack growth in a low carbon steel under tension-compression and pulsating-tension loading, *Fatigue Fracture Engng Mater. Structures*, **13**, 31–39.

(4) OGAWA, T., TOKAJI, K., and KATO, Y. (1990) Growth characteristics of large and small fatigue cracks in dual-phase stainless steel, *Trans Japan Soc. mech. Engrs*, **56**, 752–758 (in Japanese).

(5) DE LOS RIOS, E. R., MOHAMED, H. J., and MILLER, K. J. (1985) A micro-mechanics analysis for short fatigue crack growth, *Fatigue Fracture Engng Mater. Structures*, **8**, 49–63.

(6) CHAN, K. S. (1987) Micromechanics of small fatigue cracks: a model, *Fatigue '87*, Vol. 3, pp. 1801–1818.

(7) COX, B. N. and MORRIS, W. L. (1987) A probabilistic model of short fatigue crack growth, *Fatigue Fracture Engng Mater. Structures*, **10**, 419–428.

(8) COX, B. N. and MORRIS, W. L. (1987) Model-based statistical analysis of short fatigue crack growth in Ti 6Al-2Sn-4Zr-6Mo, *Fatigue Fracture Engng Mater. Structures*, **10**, 429–446.

(9) NAVARRO, A. and DE LOS RIOS, E. R. (1987) A model for short fatigue crack propagation with an interpretation of the short-long crack transition, *Fatigue Fracture Engng Mater. Structures*, **10**, 169–186.

(10) NAVARRO, A. and DE LOS RIOS, E. R. (1988) A microstructurally short fatigue crack growth equation, *Fatigue Fracture Engng Mater. Structures*, **11**, 383–396.

(11) AKINIWA, Y. and TANAKA, K. (1989) A Monte Carlo simulation of the propagation of microstructurally small fatigue cracks. *J. Soc. Mater. Sci. Japan*, **38**, 1169–1175 (in Japanese).

(12) TOKAJI, K., OGAWA, T., HARADA, Y., and ANDO, Z. (1986) Limitations of linear elastic fracture mechanics in respect of small fatigue cracks and microstructure, *Fatigue Fracture Engng Mater. Structures*, **9**, 1–14.

(13) TOKAJI, K., OGAWA, T., and HARADA, Y. (1986) The growth of small fatigue cracks in a low carbon steel; the effect of microstructure and limitations of linear elastic fracture mechanics, *Fatigue Fracture Engng Mater. Structures*, **9**, 205–217.

(14) TOKAJI, K. and OGAWA, T. (1988) The growth of microstructurally small fatigue cracks in a ferritic-pearlitic steel, *Fatigue Fracture Engng Mater. Structures*, **11**, 331–342.

(15) TOKAJI, K. and OGAWA, T. (1990) The effects of stress ratio on the growth behaviour of small fatigue cracks in an aluminum alloy 7075-T6 (with special interest in Stage I crack growth), *Fatigue Fracture Engng Mater. Structures*, **13**, 411–421.

(16) TOKAJI, K., OGAWA, T., KAMEYAMA, Y., and KATO, Y. (1990) Small fatigue crack growth behaviour and its statistical properties in a pure titanium, *Fatigue '90*, Vol. 2, pp. 1091–1096.

(17) MINAKAWA, K., MATSUO, Y., and McEVILY, A. J. (1982) The influence of a duplex microstructure in steels on fatigue crack growth in the near-threshold region, *Met. Trans*, **13A**, 439–445.

(18) DUTTA, V. B., SURESH, S., and RITCHIE, R. O. (1984) Fatigue crack propagation in dual-phase steels: effects of ferritic-martensitic microstructures on crack path morphology, *Met. Trans*, **15A**, 1193–1207.

(19) SHANG, J. K., TZOU, J. L., and RITCHIE, R. O. (1987) Role of crack tip shielding in the initiation and growth of long and small fatigue cracks in composite microstructures. *Met. Trans*, **18A**, 1613–1627.

(20) DE LOS RIOS, E. R., TANG, Z., and MILLER, K. J. (1984) Short crack fatigue behaviour in a medium carbon steel, *Fatigue Engng Mater. Structures*, **7**, 97–108.

(21) SURESH, S. (1983) Crack deflection: implications for the growth of long and short fatigue cracks, *Met. Trans*, **14A**, 2375–2385.

(22) BROWN, C. W., KING, J. E., and HICKS, M. A. (1984) Effects of microstructure on long and short crack growth in nickel base superalloys, *Met. Sci.*, **18**, 374–380.

(23) GERDES, C., GYSLER, A., and LUTJERING, G. (1984) Propagation of small surface cracks in Ti alloys, *Fatigue crack growth threshold concepts* (Edited by D. L. Davidson and S. Suresh), AIME, Warrendale, pp. 465–478.

(24) WAGNER, L., GREGORY, J. K., GYSLER, A., and LUTJERING, G. (1986) Propagation behaviour of short cracks in a Ti-8.6Al alloy, *Small fatigue cracks* (Edited by R. O. Ritchie and J. Lankford), The Metallurgical Society, Warrendale, pp. 117–128.

(25) BU, R. and STEPHENS, R. I. (1986) Comparison of short and long fatigue crack growth in 7075-T6 aluminum, *Fatigue Fracture Engng Mater. Structures*, **9**, 35–48.

(26) TAYLOR, D. and KNOTT, J. F. (1981) Fatigue crack propagation behaviour of short cracks: the effect of microstructure, *Fatigue Engng Mater. Structures*, **4**, 147–155.

(27) TAYLOR, D. (1986) Fatigue of short cracks: the limitations of fracture mechanics, *The behaviour of short fatigue cracks*, EGF 1 (Edited by K. J. Miller and E. R. de los Rios), Mechanical Engineering Publications, London, pp. 479–490.