# FATIGUE CRACK PROPAGATION MECHANISMS MAP FOR LOW ALLOY STRUCTURAL STEELS

Zhang Pingsheng (张平生) Hu Zhizhong (胡志忠) Zhou Huijiu (周惠久)
Xi'an Jiaotong University, China

## INTRODUCTION

The fracture mechanisms map first introduced by M.F. Ashby is becoming quite widely accepted[1,2]. The extension of this concept of Ashby's map to fatigue fracture has been studied recently.

On the da/dN-ΔK plane, the relationship between da/dN and fatigue fracture mechanisms for a given material was offered by R.O. Ritchie[3]. After the fashion of his work, C.Masuda et al. have constructed fatigue fracture mechanisms maps (or fatigue crack propagation mechanisms maps) for F/P steels, high and low temperature tempered steels, etc[4]. Another way of making FCPM maps was presented by us[5] and H. Kobayashi[6] separately. $K_{max}$ (or ΔK) and tempering temperature as a material parameter of a given steel were employed in Kobayashi's map[6], while in our maps the material parameter used is the ratio of $\sigma_{y,s}/K_{1c}$[5]. Our maps are constructed with the intention to correlate fatigue crack propagation rate da/dN and micromechanisms of fracture with the material property $\sigma_{y.s}/K_{1c}$ and loading factor ΔK ($K_{max}$). Data are compiled from tests of medium or low carbon structural alloy steels at room temperature in air. The way of FCPM map construction is discussed in this paper and some of the maps are presented as well.

## THE METHOD OF MAKING FCPM MAP

The most important parameter of macro-features for fatigue crack propagation is the crack growth rate da/dN. Although da/dN is dependent on many factors, the fundamental ones are material property, environment (test temperature and surrounding medium) and stress-strain state (related to loading condition and sample geometry). When the environment is kept constant, close attention should be paid only on the effect of the material factor (M) and stress intensity factor $\Delta K$ or $K_{max}$. If a three-dimensional space diagram with the axes of da/dN, M and $\Delta K$ or $K_{max}$ was drawn, da/dN is a spatial curved plane, as shown in Fig. 1. The castshadows of da/dN curved plane cut by constant M planes are a group of da/dN-$\Delta K$(or $K_{max}$) curves on the da/dN-$\Delta K$ or $K_{max}$ plane. When cut by constant $\Delta K$ (or $K_{max}$) planes, a group of da/dN-M curves on da/dN-M plane are created. The projections of intersection of curved plane and constant da/dN planes on M-$\Delta K$ (or $K_{max}$) plane are another series of curves corresponding to different da/dN as shown on the bottom of Fig. 1. We can see clearly regions with different da/dN levels in this M-$\Delta K$ (or $K_{max}$) plane. Because da/dN is closely related to fracture mechanisms, it is our basic point of view that the FCPM map should be constructed on the two-dimensional plane of M and $\Delta K$(or $K_{max}$) for which some comments have been given by K. Iida and H. Kobayashi[7].

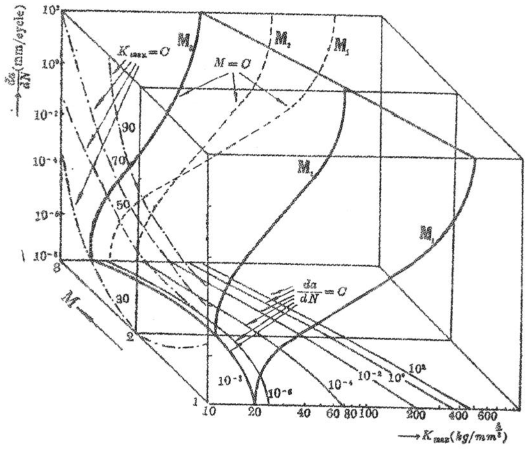

Fig. 1 Schematic illustration of da/dN curved plane

It is clear that a material parameter other than tempering temperature should be selected if we wish to make a FCPM map that could be used not only for steels at different tempering states but also for a group of steels with different structures.

$\sigma_{y,s}$ and $K_{1c}$ are important material parameters both in relation to design and to fatigue fracture. It is well known that fatigue crack propagation mechanism may be different for materials with different $\sigma_{y,s}$ or $K_{1c}$. The $K_{1c}/\sigma_{y,s}$ ratio is a parameter related to the critical plastic zone size at the crack tip when unstable propagation of fatigue crack is impending. $K_{1c}/\sigma_{y,s}$ is an important parameter in the ratio analysis diagram (RAD) for fracture control design in mechanical engineering[8]. It has also been used on fatigue design procedures for welded structural steels.[9] Thus, we have chosen $\sigma_{y,s}/K_{1c}$ as a material parameter for map construction. Of course, further work has to be done to find a more appropriate material parameter.

The fracture micro-mechanisms were determined by electron fractographic observations. They can be divided into three types:

(1) "Structure sensitive" transgranular mechanism (STG) and intergranular fracture mechanism (SIG) at low crack growth rate region (The STG is called "slip plane separation" showing the like-cleavage pattern or the "hill and valley" pattern roughly parallel to the crack propagation direction).

(2) Fatigue striation mechanism (S) at medium crack growth rate region.

(3) At high crack growth rate region, the static type fracture mechanisms including dimples (D), cleavage or quasi-cleavage (C) and intergranular fracture (IG).

## FATIGUE CRACK PROPAGATION MECHANISMS MAP

Fig. 2 (R~0.35) and Fig. 3 (R≲0.1) are FCPM maps with $\sigma_{y,s}/K_{1c}$ and $\Delta K$ (or $K_{max}$) coordinates in log-log scale. For a given material state the fatigue crack propagation process can be described by a horizontal straight line crossing different fracture mechanism regimes, in which the fracture mechanisms are labeled. From the maps it is shown that the variations of fracture mechanism during the whole crack propagation process can be expressed by three modes for different material characterstics.

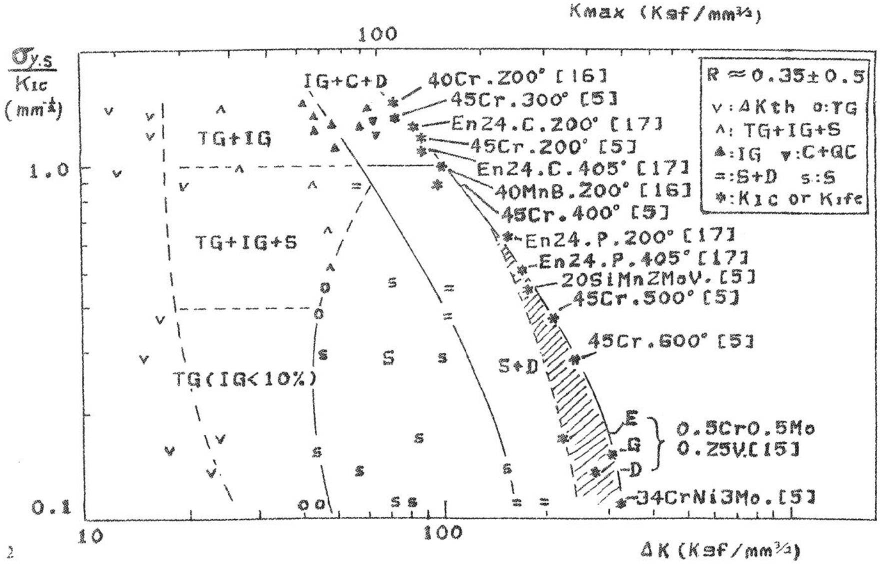

Fig. 2 a FCPM map. R~0.35

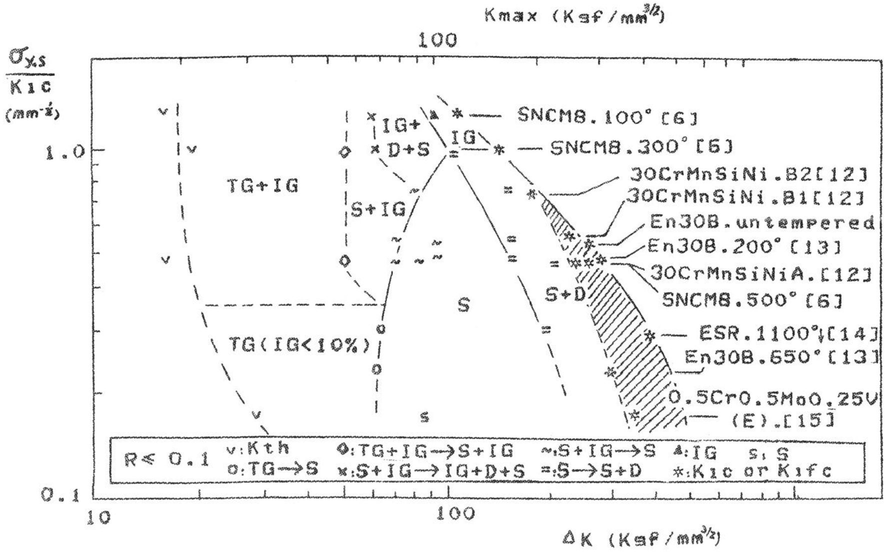

Fig. 3 a FCPM map. R≦0.1

For low values of $\sigma_{y,s}/K_{1c}$, the mode is

$$\boxed{STG} \rightarrow \boxed{STG + S + SIG\ (\leq 10\%)} \rightarrow \boxed{S} \rightarrow \boxed{S + D} \rightarrow \boxed{D}$$

For medium values of $\sigma_{y,s}/K_{1c}$, the mode is

$$\boxed{STG + SIG} \rightarrow \boxed{S + SIG\ (30\text{--}50\%)} \rightarrow \boxed{S} \rightarrow \boxed{S + D} \rightarrow \boxed{D}$$

While for high value of $\sigma_{y,s}/K_{1c}$, the striation mechanism region is absent. The mode is

$$\boxed{SIG + STG} \rightarrow \boxed{IG + S} \rightarrow \boxed{IG + C + D}$$

It is interesting to find upon what condition a given fracture mechanism will occur or change from one to another. Fig. 4 was made from a part of the data (d known) compiled in this paper. It is another type of FCPM map with $K_{max}/K_{1c}$ versus $R_p^r/d$. $R_p^r$ is the reversed plastic zone size, $\frac{1}{3\pi}(\Delta K/2\sigma_{y,s})^2$, d is the grain size of the material. In Fig. 4 the different

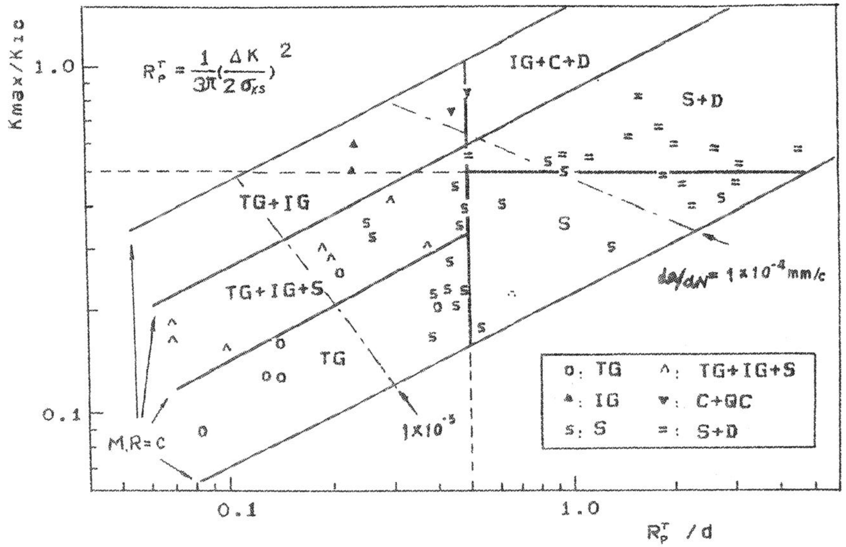

Fig. 4 another type of FCPM map

fracture mechanisms are as follows:

(1) For $(K_{max}/K_{1c}) \geqq 0.5$ region, static type fracture mechanisms, plus striation.

(2) For $(R_p^r/d) \leqq 0.5$ region, STG and SIG.

(3) For $(R_p^r/d) \geqq 0.5$ region and $(K_{max}/K_{1c}) \leqq 0.5$ region, striation is the unique fatigue mechanism ( ~100% F.A.P.). The above rule agrees well with Fig. 2 and Fig.3. For high $\sigma_{y,s}/K_{1c}$ values, for example, in low temperature tempered steel, $\sigma_{y,s}$ is high and $K_{1c}$ is low, it is difficult to find the crack propagation mode with striation mechanism only.

When $\Delta K$(or $K_{max}$) is kept constant, why should fracture mechanism change from STG to SIG with $\sigma_{y,s}/K_{1c}$ increasing? V. Weiss gave[10]

$$K_{1c} = \sigma_{y,s}\left[\left(\frac{\varepsilon_f}{\varepsilon_y}\right)^{1+n} - 1\right]^{1/2} (\pi\rho_0)^{1/2} \tag{1}$$

where $\rho_0$ is the critical curvature radius at crack tip, $\varepsilon_f$ is fracture strain. From (1) $K_{1c}/\sigma_{y,s}$ is regarded as a parameter related to the ductility. It has been pointed out by us[11a] and C.J. Beevers[11b] that SIG only occurs under high three-dimensional stress, e.g. in hard plastic constraint. On the contrary the STG occurs in plane-stress condition. It is likely that the plastic constraint at the fatigue crack tip should be increasing if $\sigma_{y,s}/K_{1c}$ is increasing. Thus, the fracture mechanism will change from STG to SIG.

Further work need be done to find out how good the agreement will be for the FCPM maps with more experimental data.

## CONCLUSION

(1) The FCPM maps give an overview of the micro-mechanisms and their variation by which low alloy structural steels may fracture by fatigue, and help identify the one most likely to be dominant in a given experiment or an engineering application.

(2) The FCPM maps should be beneficial to the fatigue failure analysis as well as the selection and improvement of materials.

## REFERENCES

[1] M.F. Ashby, Proc. ICF4, Waterloo, 11 (1977).

[2] A.L.W. Collins and D.M.R. Taplin, J. Mater Sci., 13, 2249 (1978).

[3] R.O. Ritchie, Met. Sci., 11, 368 (1977).

[4] Masuda, C., Tanaka, K., and Nishijima, S., Trans. Japan. Soc. Mech. Engr., 46, 247 (1980).

[5] Zhang. P., Hu. Z., and Zhou. H., J. Xian Jiaotong Univ., 14 (No. 3), 31 (1980).

[6] Kobayashi, H., Fujita, K., Komine, A. and Nakazawa, H., J. Soc. Mater. Sci. Japan, 29, 580 (1980).

[7] Iida, K., and Kobayashi, H., JHPI, 19, 214 (1981).

[8] ASM. Metals Handbook, Vol. 10, 8th Edition P. 42 (1975).

[9] T.W. Crooker and E.A. Lange, Weld Inst Conf. Fatigue Weld Struct. Brighton, Paper 15 (1970).

[10] V. Weiss, Mechanical Behavior of Materials, JSMS Vol. 1, P. 456 (1972)

[11a]C.J. Beevers, Matal. Sci., 14, 418 (1980).

[11b]Zhang. P., Hu. Z. and Jing. D., J. Xian Jiaotong Univ., 14, No.4, 63 (1980).

[12] Sun. F., Liao. C., Lan. F., Liu. C. and Liu J., Acta Metallurgica Sinica, 16, 140 (1980).

[13] R.O. Ritchie and J.F. Knott, Mechanics and Mechanisms of Crack Growth, P. 201 (1973).

[14] R.C. Andrew, G.M. Weston and J.C. Ritter, Metal Sci., 13, 78 (1979)

[15] J. P. Benson and D.V. Edmonds Mater Sci. Eng., 38, 179 (1979), Metal Sci., 12, 223 (1978).

[16] Technical Report of Xian Jiaotong Univ., to be published.

[17] P.R.V. Evans, N.B. Owen and B.E. Hopkins, Eng. Fract. Mech., 3, 463 (1971).