The effect of multi scale dominating region on brittle fracture

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Abstract

In this paper, based on previously obtained experimental and theoretical results related to brittle fracture and interactive dislocation dynamics, multi scale effect of dominating region on brittle fracture were discussed from the view point of scale similarity of mechanical properties. From this research, it was found that the nearest effective mechanical factor qualitatively affects an essential mechanical behavior of materials. On the other hand, other surrounded mechanical factors quantitatively affect mechanical behaviors of materials in the manner of scale effect and mechanical similarity is held independent of the existence of these surrounded mechanical factors.

Key words: trigger point, brittle fracture, dislocation free zone, hydrogen embrittlement, similarity law, scale effect

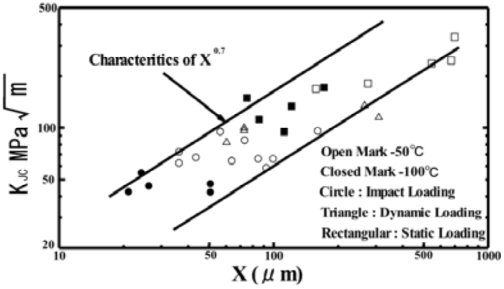
1.INTRODUCTION

As a dominating region of brittle fracture, the concepts such as process region and εregion has been proposed[1-3]. Especially, by defining the dominating region of brittle-ductile fracture as ε, the effect of grain size, notch tip radius on fracture strength have been systematically predicted[2]. Furthermore, theoretical results based on micro mechanics such as dislocation dynamics was found to accurately predict experimental results in the form of similarity scales[4]. If these mechanical similarities which hold through various scale ranges have fractal characteristics between them, the construction of theoretical foundation which accurately predict the occurrence of the complex physical phenomenon will be possible.

In this paper, based on previously obtained experimental and theoretical results, multi scale effect of dominating region on brittle fracture were discussed from the view point of scale similarity of mechanical properties.

2.TRIGGER POINT OF BRITTLE FRACTURE AND FRACTURE TOUGHNESS

The experimental relationship between fracture toughness and trigger point for steel was systematically investigated[5] and it was compared with the theoretical result on the relationship between dislocation free zone (DFZ) for dynamic dislocation groups emitted from a stressed source and fracture toughness as shown in Fig.1[4]. Data band indicated by solid lines are the characteristics of ten times magnified theoretical results on the relationship between dislocation free zone (DFZ) and fracture toughness[5].



Theoretical
h=10~100μm

Experimental
X=10~1000 μm

Fig.1 The relationship between fracture toughness and trigger points (experimental data) and that between fracture toughness and dislocation free zone (the band by solid lines)

The definition of trigger point[5] and dislocation free zone[6] were shown in Figs.2 and 3. Dislocation free zone may correspond to trigger point. Both of these relationships show that, however there are ten times differences in scale between them, experimental results are in good agreement with theoretical results at the state of similarity. Under the actual condition, there is not a slip line but are multiple slip lines around a crack tip as is shown in Fig.4.However, the theoretical analysis on the mechanical interaction of the stress concentration for multiple slip lines which include static dislocation groups is found to be qualitatively in good with that for a single slip line which includes static dislocation groups. And there is quantitative difference in mechanical intensity and effective scale between them[7]. From this result, the quantitative difference in scale between experimental and theoretical relationships as shown in Fig.1 will come from the multiple effect of many slip lines on the trigger point which keep mechanically similarity between the case for single and multiple slip lines. These results show that microscopic region which corresponds to DFZ is an origin of fracture dominant region.

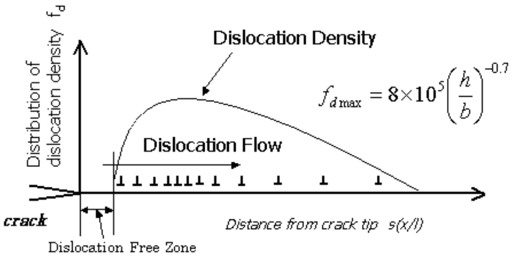


Fig.2 The inverse pile up of dislocation groups at the end of dislocation free zone around a crack tip. h:dislocation free zone, b:Burger's vector, f_{dmax}:The maximum dislocation density.

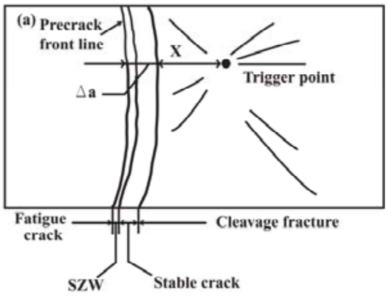


Fig.3 A trigger point located at a distance of x from a crack tip

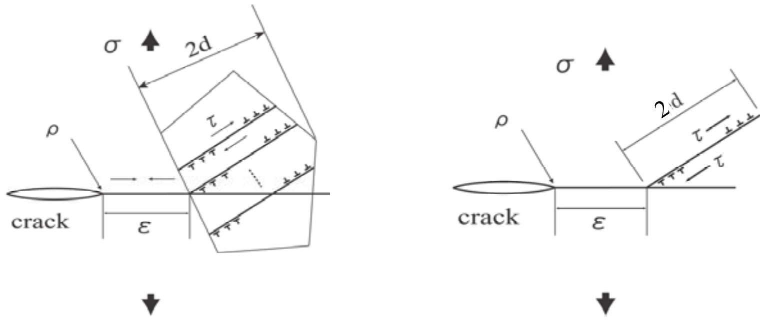


Fig.4 The analytical model of the interaction between a crack and multi slip bands.

In this analysis, the basic equation of dislocation motion in a slip line is written by eqn. (1).

$$V_i = M\tau_{eff,i}^{m} \qquad (1)$$

Where$\tau_{eff,i}$ = the effective stress exerted on each individual dislocation in terms of applied shear stress; m = materials constant; and i = index of dislocation in order of emitting from the source.

M is written as

$$M = V_0(1/\tau_0^{*})^{m} \qquad (2)$$

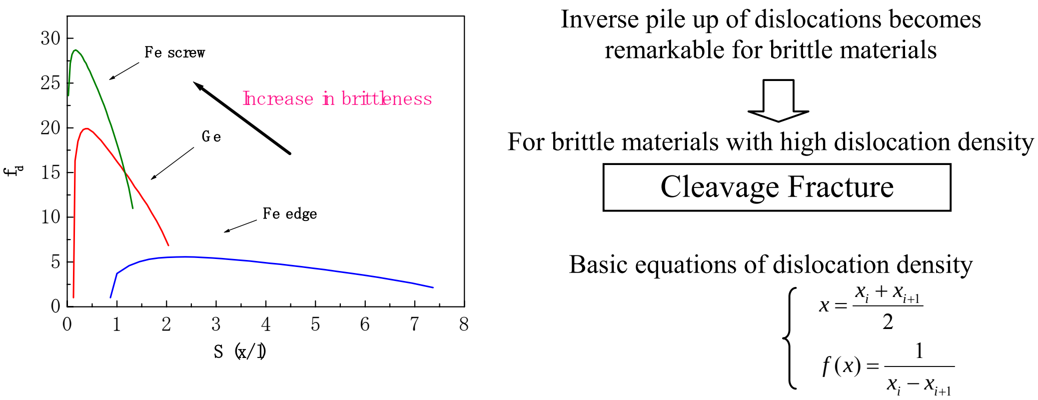
Where τ_0^* = specific shear stress required to move an isolated dislocation with a velocity of 1 cm/s; and V_0 = 1 cm/s.

In this analysis, the effective stress exerted on the ith dislocation is written by equation (3).

$$\tau_{eff,i} = \dot{\tau} t\left(\sqrt{\frac{a}{x_i}}+1\right)+\left[A\sum_{\substack{j=1\\ i\neq j}}^{n}\frac{1}{x_i-x_j}-\frac{A}{2x_i}-A\sum_{\substack{j=1\\ i\neq j}}^{n}\left(\frac{1}{x_i+\sqrt{x_i x_j}}\right)\right] \tag{3}$$

Where $A=\begin{cases}\mu b/2\pi(1-\nu) & \text{For edge dislocation}\\ \mu b/2\pi & \text{For screw dislocation}\end{cases}$

These computer analysis showed the inverse pile up of dislocation density occurs at the end of dislocation free zone which results in high stress concentration[4,6] as shown in Fig.5. Based on this result, the relationship between fracture toughness and dislocation free zone was obtained as shown in Fig.1[4].



Inverse pile up of dislocations becomes remarkable for brittle materials

For brittle materials with high dislocation density

Cleavage Fracture

Basic equations of dislocation density

$$\begin{cases} x=\dfrac{x_i+x_{i+1}}{2}\\ f(x)=\dfrac{1}{x_i-x_{i+1}}\end{cases}$$

Fig.5 Ductile-brittle transition on the distribution of dislocation density.

3.THE MECHANICAL INTERACTION BETWEEN DISLOCATIONS AND HYDROGEN

Previously, to clarify the mechanism of hydrogen embrittlement for ductile materials, the analysis of mechanical interaction between dynamic dislocation groups and hydrogen were conducted based on the physical model as shown in Fig.6[8].

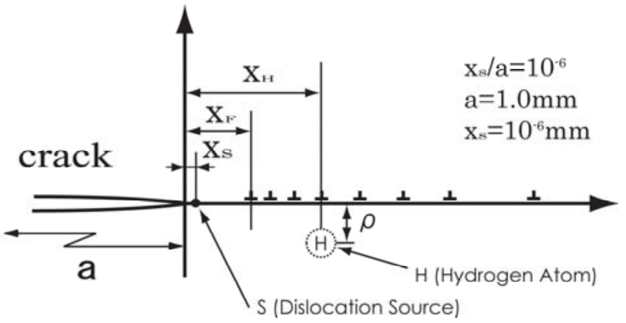


Fig.6 Physical model of dislocation emission and the interaction of dislocations and a super hydrogen

The basic equation is written by eqn.(1). In this analysis, effective stress exerted on each dislocation in a slip line with mechanical interaction by hydrogen is written by

$$\tau_{eff,i} = \dot{\tau}\, t\left(\sqrt{\frac{a}{x_i}}+1\right)+\left[A\sum_{\substack{j=1\\ i\neq j}}^{n}\frac{1}{x_i-x_j}-\frac{A}{2x_i}-A\sum_{\substack{j=1\\ i\neq j}}^{n}\left(\frac{1}{x_i+\sqrt{x_i x_j}}\right)\right]-\frac{2A^{*}\rho\left(x_i-x_h\right)}{\left[\left(x_i-x_h\right)^2+\rho^2\right]^2} \qquad (4)$$

Where $A=\begin{cases}\mu b/2\pi(1-\nu)\\ \mu b/2\pi\end{cases}$,

The fourth term of right hand side of eqn.(4) is an interactive one between dislocation groups in a slip line and hydrogen cluster which is represented by a super hydrogen.

In this analysis[8], concerning the numerical results of distribution of effective stress exerted on each dislocation $\tau_{eff,i}(x)$, the characteristic of locally decreasing in$\tau_{eff,i}(x)$ around the trapped region of dislocations by hydrogen was found out which results in high dislocation concentration at this region[8] and in brittle fracture related to hydrogen embrittlement for ductile materials[9] as is shown in Figs.7 and 8. The effective scale of the fluctuation of$\tau_{eff,i}(x)$ equals to the order of 5μm.

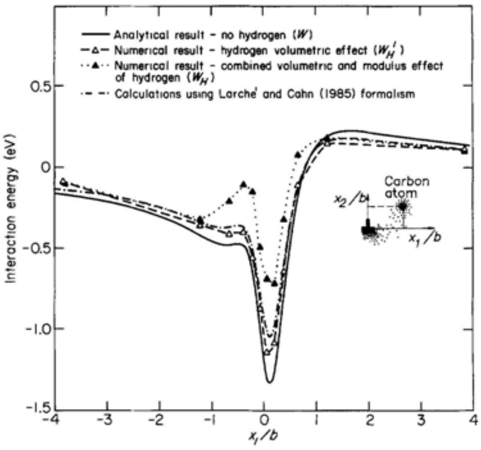


Fig.9 The interaction energy between a dislocation and hydrogen obtained by Sofronis et.al[10].

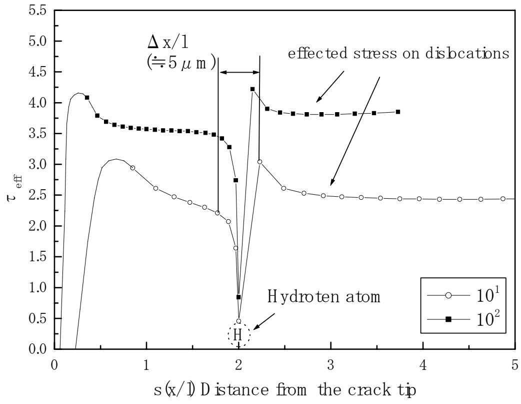


Fig.7 The distribution of effective stress exerted on each dislocation under interaction with other dislocations and hydrogen.

On the other hand, the analysis of effective stress field caused by the interaction between single dislocation and hydrogen was conducted[10] as is shown in Fig.9[10]. The result obtained by this analysis is qualitatively in good agreement with that for dislocation groups dynamics as shown in Fig.7. However, quantitatively, the effective scale of the fluctuation for the former case equals to the order of Burger's vector(3x10^{-7}mm). That is, there is for order difference in mechanically effective scale between them. These results show the law of mechanically similarity exists between the relationship of mechanical interaction between single dislocation and hydrogen and that between dislocation groups and hydrogen solved by the equation which includes non linear interactive term given by eqn.(4). However, there is ten to four times difference in mechanically effective scale between them ranging from nano to mezzo scale. This also shows that essential mechanical factor on the occurrence of hydrogen embrittlement for a ductile material is a mechanical interaction between a dislocation and hydrogen. Furthermore, it was found that non linear terms from the second to fourth in eqn.(4) have the property of numerical similarity independent of the number of dislocations on a slip line.

Therefore, the nearest effective mechanical factor qualitatively affects an essential mechanical behavior of materials. On the other hand, other surrounded mechanical factors quantitatively affect mechanical behaviors of materials in the manner of scale effect and mechanical similarity is held independent of the existence of these surrounded mechanical factors.

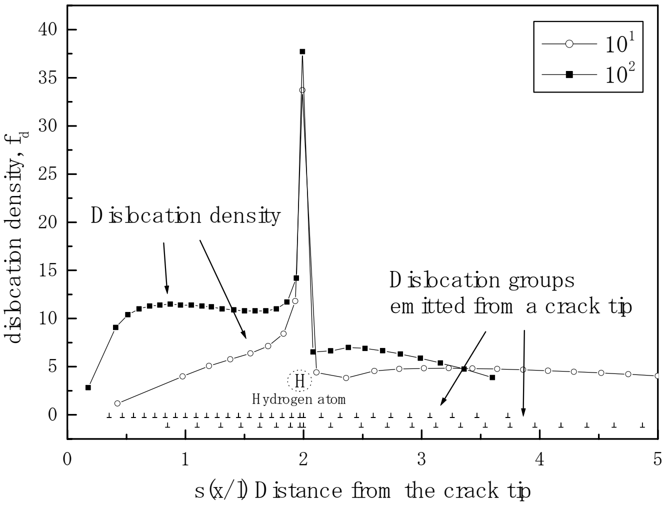


Fig.8 Dislocation pile up behavior in the dislocation array around hydrogen with parameter of applied stress rate.

4.CONCLUSION

1) Concerning mechanical interaction between dislocation groups on a slip line, the law of mechanical similarity on the relationship between dislocation free zone and fracture toughness and that between experimental trigger point and fracture toughness was found to exist, however there are ten times difference in scale between them. This will come from the effect of multiple slip lines on these relationships which keep mechanically similarity between cases for single and multiple slip lines. These results show that microscopic region which corresponds to DFZ on a slip line is an origin of fracture dominant region.

2) Concerning the mechanical interaction between dislocations and hydrogen, the law of mechanical similarity exists in the mechanical interaction such as stress fluctuation and concentration between single dislocation and hydrogen and that between dislocation groups and hydrogen cluster obtained by the equation which includes non linear interactive term given by eqn.(4), however there are ten to four times difference in scale between them, that is, ranging from nano to mezzo scale.

3) The nearest effective mechanical factor dominates mechanical behavior of materials as an essential qualitative effective factor. On the other hand, other surrounded mechanical factors affect mechanical behaviors of materials as qualitative effective factors in the manner of scale effect and mechanical similarity is held independent of the existence of these surrounded mechanical factors.

Finding of these mechanical similarities may enable us to find out essential effective factors on the occurrence of fracture.

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In this paper, based on previously obtained experimental and theoretical results, multi scale effect of dominating region on brittle fracture were discussed from the view point of scale similarity of mechanical properties. The following results were obtained.

1) Concerning mechanical interaction between dislocation groups on a slip line, the law of mechanical similarity on the relationship between dislocation free zone and fracture toughness and that between experimental trigger point and fracture toughness was found to exist, however there are ten times difference in scale between them. This will come from the effect of multiple slip lines on these relationships which keep mechanically similarity between cases for single and multiple slip lines. These results show that microscopic region which corresponds to DFZ on a slip line is an origin of fracture dominant region.
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