Yield Strength and Stacking Fault Energy on Fatigue Crack Propagation

Kazuo HONDA and Tetsuro KONAGA

Department of Mechanical Engineering

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Synopsis

It is very important to clarify the question whether fatigue crack propagation will be affected by mechanical propaties or other propaties of materials. In the present paper the authors studied in relation of yield strength and stacking fault energy to rate of fatigue crack propagation. α-brass were chosen for the investigation because they provided sufficient range in both quantities of interest that either could be varied independently of the other.

Fatigue tests were carried out under full bending moment of flat specimens with V-shape notch. Chosen stress levels were 0.6 σ_y and 0.8 σ_y in which σ_y is yield strength, rate of fatigue crack propagation was evaluated from the second stage of the curve of fatigue crack propagation.

The dependence of the rate on stacking fault energy γ was found to be $dl/dN = C \cdot \gamma^n$. But dl/dN did not systematically to change in yield strength. Thus, γ is concluded to be the controlling variable.

§ 1. Introduction

A subject point of controversy in current work concerning fatigue crack propagation relates to the effects of strength and stacking fault energy.

That is, Holden[1], Grosskreutz[2),3)] and Taira[4),5)] have shown that subgrain structure is introduced during fatigue process, and cracking is aided through propagation along subgrain boundaries. Therefore, lowering γ to interfere with subgrain structure formation would be expected to delay the rate. It is a general rule, too, that resistance to fatigue cracking increase with strength. σ_y and γ increase and decrease with pct of zinc contents in α-brass.

In this paper, the authors picked up σ_y from some strengths of material, and intended to clarify interactions between σ_y and γ in rate of fatigue crack propagation dl/dN under fatigue process in isolating stress levels of 0.6 and $0.8\sigma_y$.

§ 2. Experimental Procedures

2.1. Specimen and Fatigue Testing

The specimens used in this study were 10% Zn-, 20%Zn-and 30%Zn-brass, these mechanical properties and chemical compositions were shown in Tables 1 and 2. Before testing,

Table 1. Mechanical properties.

	Yield strength (kg/mm^2)	Tensile Strength (kg/mm^2)	Elongation (%)	Grain size (μ)
10% Zn-brass	5.5	24.1	50.0	30
20% Zn-brass	5.7	25.5	66.8	30
30% Zn-brass	6.0	27.5	73.0	30

Table 2. Chemical Compositions.

	Cu	Zn	Al	Fe	Ni
10% Zn-brass	90.12	9.60	0.11	0.15	0.02
20% Zn-brass	80.54	19.17	0.09	0.12	0.08
30% Zn-brass	69.65	29.96	0.14	0.18	0.08

the specimens were annealed for 1 hr. at 400° C in air, furnace cooled, and so it was composed of the grain of about 30μ in diameter.

The shape and dimensions of the specimen are shown in Fig. 1. Stress concentration factor α of the specimen determined from the theory of Neuber was 4.0. The specimen was applied

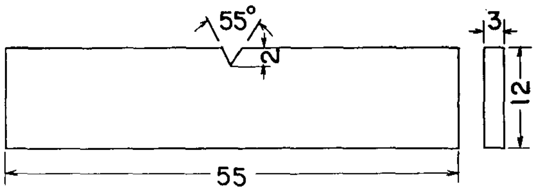

Fig. 1 Shape and dimensions of farigue specimen

full reversed stresses of 0.6 and 0.8 σ_y in the plane normal to the surface of the specimen by using the Shimadzu fatigue testing machine (UF-500 type) after it was recomposed to fit the present experiment.

2.2. X-ray Microbeam Diffraction Technique

The X-ray microbeam was collimated by double pinholes. Conditions of X-ray diffraction are listed in Table 3. Specimen was automatically oscillated around an axis of incident beam in a range of $\pm 2°$ because of large grain size (30μ), and so number of reflection on a film increase in proportion to the oscillating angle. Theoretical analysis for increasing number of reflection with the oscillating angle has been shown in previous paper.

Table 3. Conditions of X-ray microbeam diffraction technique

X-ray	Cukα
Diffraction plane (hkl)	(420)
Tube voltage (kV)	35
Tube current (mA)	15
Slit (double pinholes) ($\mu\phi$)	50—100
Divergence (rad)	0.9×10^{-3}
Resolving power (μ)	0.79
Illuminated cross section (μ)	130
Oscillation (around a vertical axis) (°)	± 2

As the analysis method of the informations about misorientation β, micro lattice strain $\Delta d/d$, dislocation density D and sub-grain size t has been offered[1], the description of the final formulae will be given here,

$$\beta = |\cos 2\theta| \cdot \Delta S_T / 2R_0 \sin\theta$$

$$\Delta d/d = \cos^2 2\theta \cdot \Delta S_R / 2R_0 \tan\theta$$

$$D = \beta / b t_0$$

$$t = t_0 \cdot m^{-\frac{2}{3}}$$

where θ is Bragg's angle, R_0 is the distance between the film and the specimen, ΔS_T and ΔS_R are the difference between the tangential and radial breadth of the spot before and after, b is Burger's vector, t_0 is grain size and m is number of micro-spot in one arc, respectively.

§ 3. Experimental Results

3.1. Fatigue Testing

As a measure of fatigue strength of the specimen, dl/dN in stress levels of 60 and 80 pct of the σ_y were adopted. The increase in crack length l, as cycles N are accumulated is shown in Figs. 2 (a) and (b). dl/dN was obtained by constructing a tangent to the l *vs* N curve in the second stage.

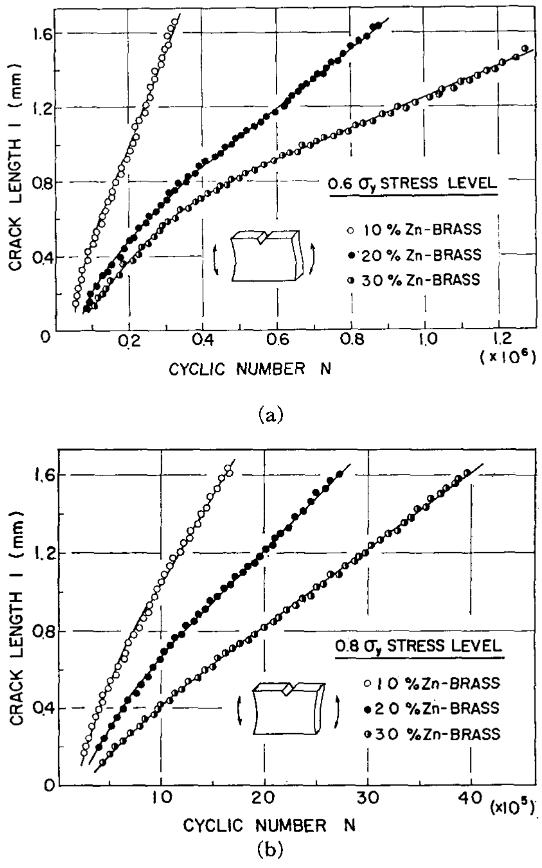

Fig. 2 Curves of fatigue crack propagation
(a) $0.6\sigma_y$ stress level.
(b) $0.8\sigma_y$ stress level.

The relation between the corresponding measures of dl/dN and stress intensity factor K is shown by straight lines on logarithmic co-ordinates in Fig. 3. K in this figure was calculated

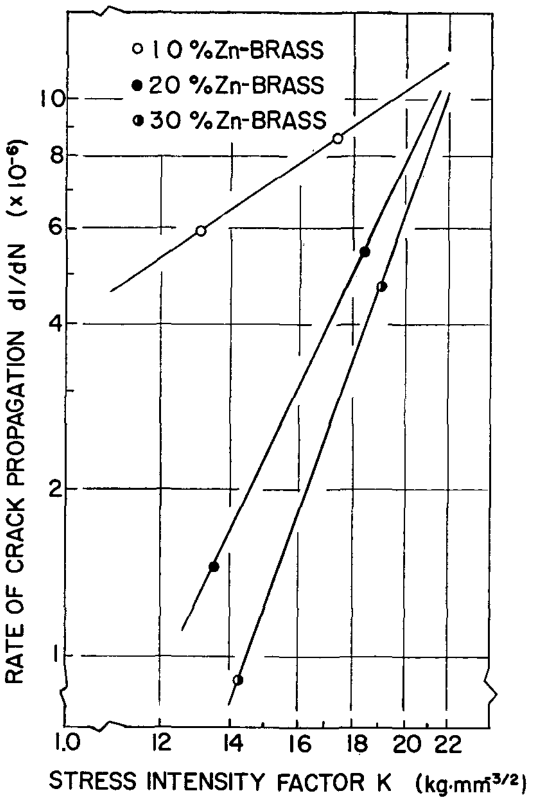

Fig. 3 Relation between rate of crack propagation and stress intensity factor.

using following equation[5]

$$K=\sigma_g\sqrt{W\tan\frac{\pi l}{W}\left\{1+0.2\left(\cos\frac{\pi l}{W}\right)^2\right\}}$$

where σ_g was the applied gross-section stress, W was breadth of the specimen, and l was the crack length.

The lines in Fig. 3, generally, can be expressed as $dl/dN=C\cdot K^n$, n and C values obtained from the slope and the point of the contact ($\log K=0$) on longitudinal axis of the line drawn through the data pionts in Fig. 3 is tabulated in Table 4. Consideration of details is deferred to a later section, but it is worth noticing that n value increase with pct of zinc contents.

§ 3.2. Observations of X-ray Microbeam Diffraction Technique

Observation of X-ray microbeam was carried out at the crack tip of 1.5mm long. Results which were obtained during fatigue process at the stress level of $0.6\sigma_y$ on β, D, $\Delta d/d$, m and t were tabulated in Table 5. From this table it is clear that values of β and D decrease in spite of roughly constant in $\Delta d/d$ with pct of zinc, and m decrease with pct of zinc and so t increase with it. The number of subdivided spots in the arc decrease also with pct of zinc. It is often reported that the existence of the microspot in the reflection suggests formation of substructure which may be closely connect with γ.

§ 4. Discussions

4.1. Effective Factors for Rate of Fatigue Crack Propagation

Table 4. Stacking fault energy and obtained results of fatigue test.

	Stacking fault energy γ (ergs/cm^2)	Rate of fatigue crack propagation dl/dN ($\times 10^{-6}$)		Cyclic nominal stress σ_n (kg/mm^2)		$dl/dN=C\,K^n$	
		$0.6\sigma_y$	$0.8\,\sigma_y$	$0.6\,\sigma_y$	$0.8\,\sigma_y$	C ($\times 10^{-3}$)	n
10% Zn-brass	40.0	6.0	8.6	3.3	4.4	1.03	1.45
20% Zn-brass	18.4	1.4	5.4	3.4	4.6	0.13	4.46
30% Zn-brass	11.3	0.9	4.8	3.6	4.8	3.02	5.62

Table 5. Observations by X-ray microbeam diffraction technique.

	Misorientation ($\times 10^{-2}$) β (rad)	Dislocation density ($\times 10^9$) D (lines/cm^2)	Micro lattice strain ($\times 10^{-3}$) $\Delta d/d$	Number of micro-spot in one arc m	Subgrain size t (μ)
10% Zn-brass	2.12	2.36	0.42	29	3.2
20% Zn-brass	1.46	1.63	0.39	18	4.4
30% Zn-brass	1.31	1.46	0.34	14	5.1

(1) Stacking Fault Energy and Yield Strength

γ is generally determined from theoretical analysis of τ_{III} (the stress at the onset of stage III in stress-strain relation[7]) and electron microscope observation of shapes of dislocation nodes.

Value of γ is divided even for the same material. γ shown in Fig. 4 is calculated from

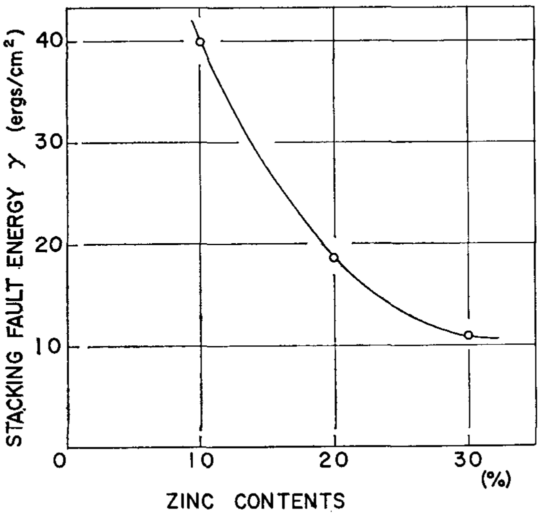

Fig. 4 Stacking fault energy in α-brass.

observation of dislocation nodes by Howie and Swan[8], and was modified by Thornton[9].

σ_y for each material is tabulated in Table 1. They are considerably lower values because of larger grain size.

(2) Stacking Fault Energy and Yield Strength for Rate of Fatigue Crack Propagation

The authors adopted a rate of fatigue crack propagation in the second stage as a scale to estimate the fatigue strength. As listed in Table 4, the rates for 10% Zn- 20% Zn- and 30 %Zn- brass are 8.6×10^{-6}, 5.4×10^{-6} and 4.8×10^{-6} in cyclic nominal stress of $0.8\sigma_y$, and 6.0×10^{-6}, 1.4×10^{-6} and 0.9×10^{-6} in cyclic nominal stress of $0.6\sigma_y$, respectively. Fig. 5 shows the relations between σ_y and dl/dN. The result seen in Fig. 5 is contrary to our forecast. That is, if the dl/dN depends on the σ_y, dl/dN in this figure must be constant because that the reversed stress was the same level of 0.6 or $0.8\sigma_y$

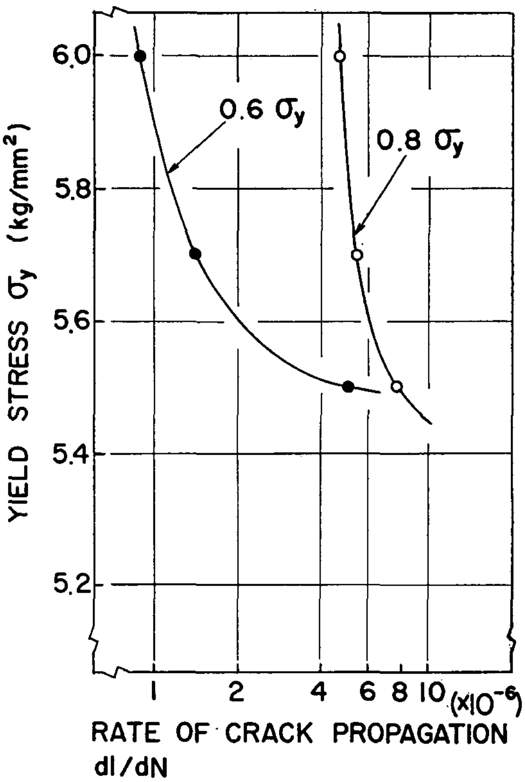

Fig. 5 Relation between rate of crack propagation and yield stress.

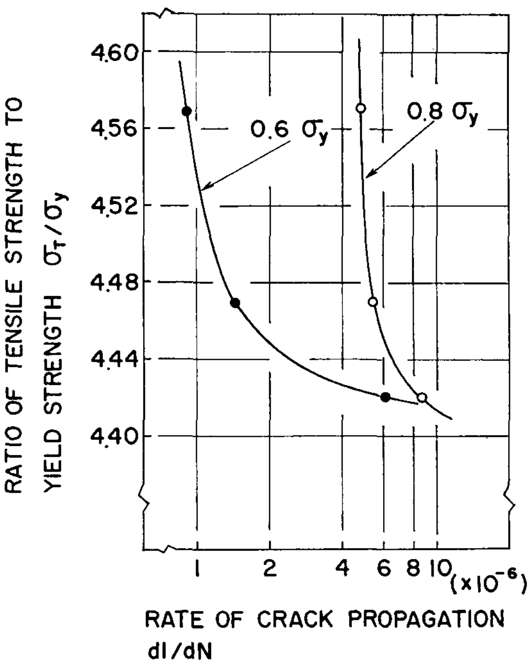

Fig. 6 Effect of ratio of tensile strength to yield stress on rate of crack propagation.

for each material. Noticing Fig. 5, however, it is obvious that dl/dN has declivity for increase of σ_y. As cause for this result some factors may be considered. Fig. 6 is an example, which expresses a relation between ratio of tensile strength to yield stress σ_T/σ_y and dl/dN. This relation is similar to the relation of Fig. 5. Accordingly, dl/dN may be influenced by the ratio of σ_T/σ_y which means strain hardening, however, it has often been reported that γ is more effective factor. Fig. 7 shows the relation

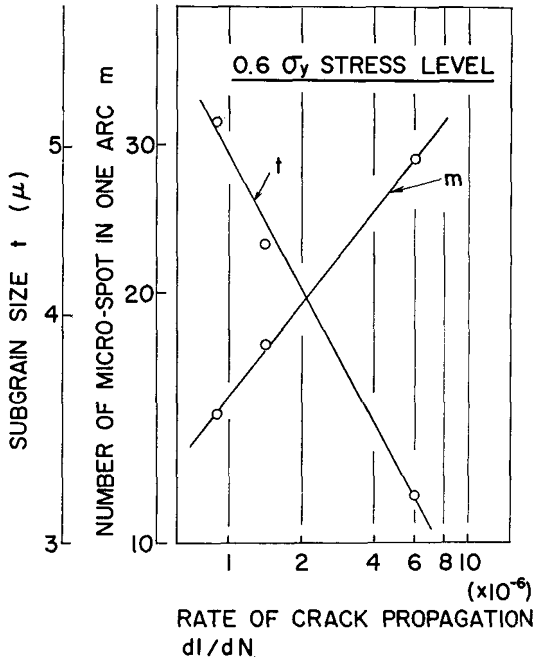

Fig. 7 Relation between informations at the crack tip obtained by X-ray microbeam diffraction technique and rate of crack propagation (0.6 σ_y stress level).

between γ and dl/dN. As shown in this figure the relations are linear in logarithumic scales, equations of $dl/dN = 1.6\times10^{-6}\cdot\gamma^{0.48}$ for $0.8\sigma_y$ and $dl/dN = 1.28\times10^{2}\cdot\gamma^{1.5}$ for $0.6\sigma_y$ were obtained.

With the comparison in Figs. 5, 6 and 7, it is conjectured that a factor which appears to correlate with the relative resistance of α-brass materials to crack propagation is the stacking fault energy, the lowest resistance being associated with the highest stacking fault energy. This correlation may also reflect an increase in strain hardening rate with decreasing stacking fault energy.

§ 4.2. Fatigue Crack Propagation and Plastically Deformed Zone at Crack Tip

Though in previous section the relation between dl/dN and γ was described, in this section the same relation is discussed from the results obtained by using X-ray microbeam diffraction technique.

In those results, misorientation β, dislocation density D and number of micro-spot in one arc m decrease with zinc contents, subgrain size t increase with it, and micro lattice strain $\Delta d/d$ is roughly constant. Among those results m and t are most important. That is, it has already been argued that γ has an influence on dl/dN through its effect on substructure development[10]. The principle detail is that cracks tend to propagate along subgrain boundary, if that path is available. By increasing γ, substructure formation is assisted and, other condition fixed, dl/dN is increase. The trend in Fig. 8 is supportant for that argument.

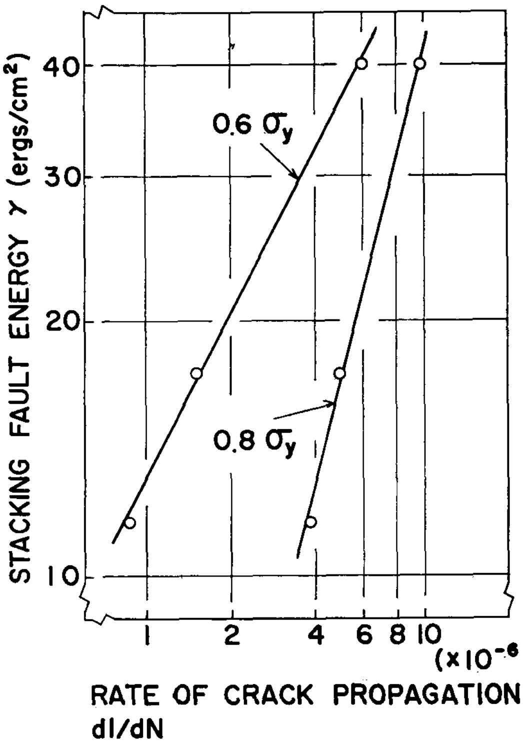

Fig. 8 Relation between rate of crack propagation and stacking fault energy.

As shown in Fig. 8, the relation between dl/dN and m and t is linear in logarithumic scales, dl/dN $= 7.2\times 10^{-10}\, m^{2.68}$ and dl/dN $= 9.1\times 10^{-4} \times t^{-4.26}$ were obtained for repeated stress level of $0.6\sigma_y$, respectively.

§ 5. Summary

In alternating bending fatigue, the dependence of rate dl/dN of fatigue crack propagation on stacking fault energy γ, number of micro-spot in one arc m and subgrain size t were found to be dl/dN $= C_1\gamma^{n_1}$, $C_2m^{n_2}$ and $C_3t^{n_3}$. But dl/dN did not systematically to change in yield strength σ_y. Thus, γ is concluded to be the controlling variable. That is, the lower dl/dN reduced is attributed to increasing difficulty in formating the substructure which facilitates cracking by separation at subgrain boundaries.

With finding reported here, however, continued doubt about the relative importance of σ_y and γ to dl/dN in α-brass seems unwarranted. Accordingly, more detailed study may be necessary.

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