THE FRACTURE-RESISTANT CHARACTERISTICS OF MEDIUM-STRENGTH PLATES WITH REGARD TO THE INITIATION, STABLE AND UNSTABLE PROPAGATION OF SURFACE CRACKS

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ABSTRACT

The fracture-resistant characteristics of 18CrNiWA and 40CrNiMoA steel plates of four thicknesses (8, 10, 12 and 14 mm) have been investigated experimentally, including initiation, stable growth and unstable propagation of surface cracks, under elastic-plastic condition. At crack initiation, the surface crack opening angle α_I of plates of various thicknesses has been found to be a constant. Before crack initiation, the value of the surface crack plastic opening angle $d\ \delta_s^P/da$ has been found to increase with an extension of Δa. During the process of stable surface crack growth after its initiation $(d\ \delta_s^P/da)_s$ has been found to be a constant; and during the process of unstable propagation $(d\ \delta_s^P/da)_u$ has been found to be another constant. $(d\ \delta_s^P/da)_u > (d\ \delta_s^P/da)_s$.

I. INTRODUCTION

In engineering practice, the damage of a structure member is caused mostly by the extension of surface cracks. It has been shown from many experimental results that for medium strength-high toughness materials a process of gradually stable crack growth takes place after its initiation, in which only with a increase of the load the surface cracks extend till unstable propagation and fracture occurs. In order to calculate reasonably the ability to sustain loads of the plates structures with cracks, it is necessary to study the fracture-resistant characteristics of steel plates with regard to the process including initiation, stable growth and unstable propagation of surface crack, under elastic-plastic condition.

For tough materials with through crack, Shih et al.[1] found that δ_c is the most suitable parameter to describe crack initiation, so is $d\,\delta_p/da$ for stable growth and $d\,\delta_c/da$ tends to a constant during the process. Chen Chi and his coworkers[2] also pointed out, that during the true extension process of a crack the crack tip plastic opening angle for these materials is a constant. Applying these conclusions to medium strength-high toughness plates with surface cracks, the surface crack opening angle at the initiation, the surface crack plastic opening angles during stable and unstable propagation all have been found to be constants, for plates of various thicknesses. Therefore, these parameters can be considered as the fracture-resistant characteristics of these plates during surface crack initiation, stable growth and unstable propagation.

The tangential point of the a-ΔP curve with the stable growth line was taken as the crack initiation point in paper [2]. By using the conditional applied load method, Cui Zhenyuan[3] measured the load P_{10} at surface crack extension $\Delta a=r_y$, i.e. the load at crack initiation (when $a_o=0.5(K_I/\sigma_{0.2})^2$ or $B=1.0(K_I/\sigma_{0.2})^2$, $\Delta a/a_o=r_y/a_o=10\%$, i.e. the surface crack relative extension is 10%), and then the crack initiation point was obtained. Since $d\,\delta/\delta=H\,da/a_o=10\%H$, P_{10} corresponds to the load at the intersection point of the P -δ curve with the secant line OP_{10} (Fig. 2, the slope of OP_{10} is equal to $1/[1+10\%H]$ of the initial tangent OA_1 slope P/δ). The crack initiation points obtained by using two methods are in excellent conformity with each other. It was verified by testing two specimens, that the crack tip is initiated under the action of the load P_{10}.

II. MATERIALS USED

The mechanical properties of the 18CrNiWA and 40CrNiMoA steel plates are listed in Table 1.

III. EXPERIMENTAL RESULTS

The ratio of width to thickness, W/B, of all specimens is 8. The effective length L of the specimens is 2W. The crack shape: a/B=0.45-0.55

(a is the depth of the crack); a/c=0.55-0.45 (c is the length of semi-major axis of the crack). The coefficient H can be obtained by the compliance calibration curve (Fig. 1)[3]. The P-δ curve of specimen No. 1-12-5

Table 1. Mechanical Properties of 18CrNiWA and 40CrNiMoA Steel Plates

	$E(MN/m^2)$	$\sigma_b(MN/m^2)$	$\sigma_{0.2}(MN/m^2)$	$\delta_5(\%)$	$\psi(\%)$
18CrNiWA	210000	1140	1010	17.4	65.3
40CrNiMoA	210000	1090	1000	17.5	65.3

is shown in Fig. 2. The conditional applied load P_{10} was obtained with the secant OP_{10} which slope is less than the slope of the initial tangent OA_1 by 16%. The calculated σ_{10} and $\sigma_{10}/\sigma_{0.2}$ are listed in Table 2. The crack length a_i acted by load P_i was calculated by using the compliance method, then $\Delta a_i=a_i-a_o$. The drawn δ_s^P-Δa curves are shown in Fig. 3 and Fig. 4. The tangential point I of the curve with the stable growth line was taken as the crack initiation point. The calculated $\sigma_I/\sigma_{0.2}$, $\alpha_I=2\tan^{-1}(\delta_I/2a_I)$, $(d\,\delta_s^P/da)_{SI}$ (during first stage of stable growth), $(d\,\delta_s^P/da)_{SII}$ (during second stage of stable growth) and $(d\,\delta_s^P/da)_u$ are listed in Table 2, 3 and 4 respectively.

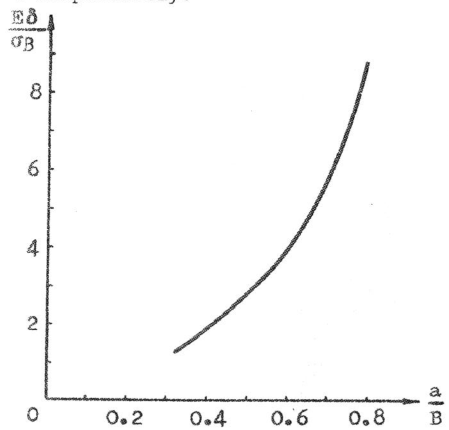


Fig. 1. Calibration curve.

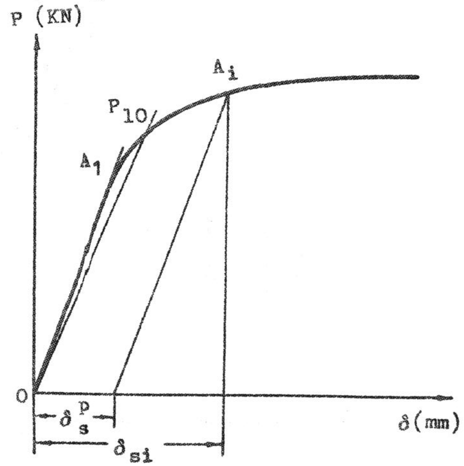
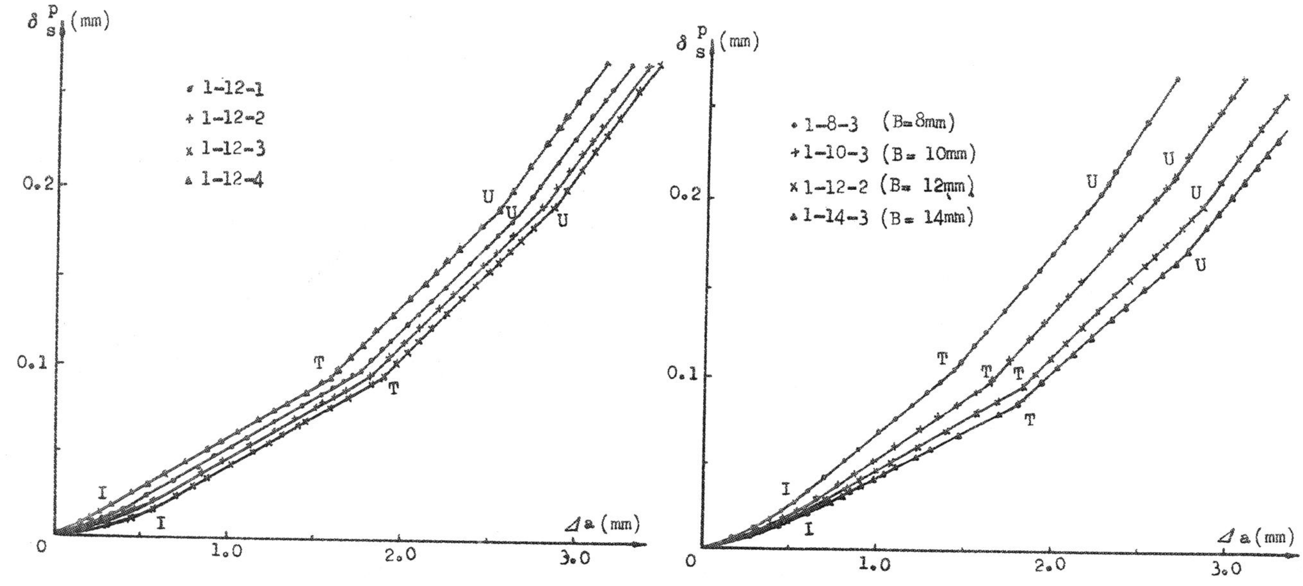


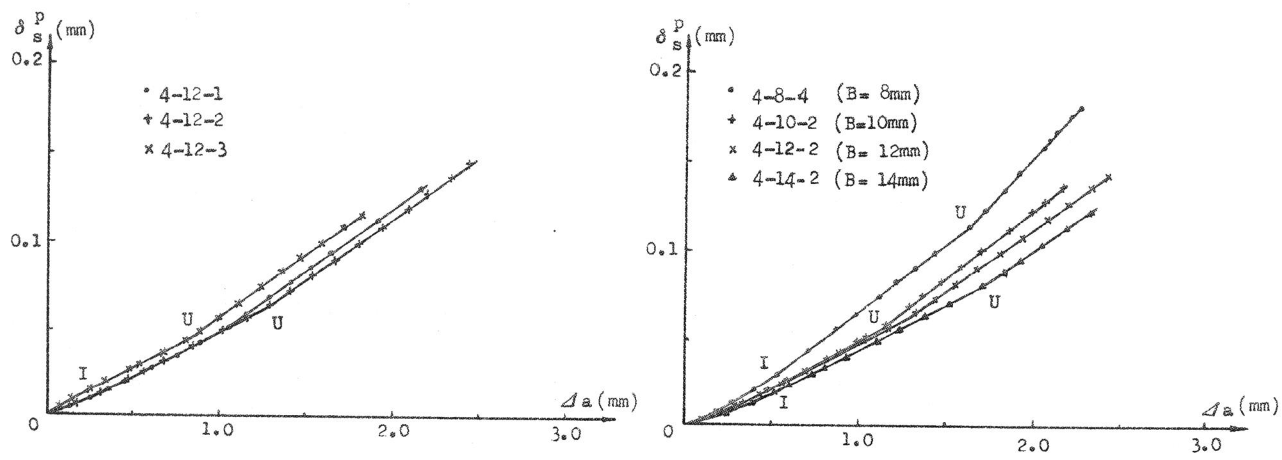
Fig. 2. P-δ curve of specimen No.1-12-5.



(a) B=12 mm

(b) B=8, 10,12 and 14 mm

Fig. 3. δ_s^P-Δa curves of 18CrNiWA steel plates



(a) B=12 mm

(b) B=8,10,12 and 14 mm

Fig. 4. δ_s^P-Δa curves of 40CrNiMoA steel plates

Table 2. The Stress Rations at the Crack Initiation Point I.

B (mm)		8	10	12	14
18CrNiWA	$\sigma_{10}/\sigma_{0.2}$	0.81-0.84	0.81-0.85	0.77-0.83	0.81-0.84
	$\sigma_I/\sigma_{0.2}$	0.86-0.88	0.80-0.83	0.76-0.81	0.79-0.83
40CrNiMoA	$\sigma_{10}/\sigma_{0.2}$	0.82-0.87	0.84-0.89	0.84-0.86	0.73-0.82
	$\sigma_I/\sigma_{0.2}$	0.82-0.85	0.83-0.88	0.80-0.84	0.77-0.80

Table 3. The Surface Crack Opening Angles α_I at Crack Initiation. (°)

B (mm)	8	10	12	14	
18CrNiWA	1.1-1.3	1.1-1.3	1.1-1.3	1.1-1.2	$\bar{\alpha}_I$=1.2±0.1
40CrNiMoA	1.2-1.3	1.2	1.1-1.2	1.2-1.3	$\bar{\alpha}_I$=1.2±0.1

Table 4. The Surface Crack Plastic Opening Angles $d\delta_s^P/da$ during Crack Extension (rad)

B (mm)		8	10	12	14
18CrNiWA	$(d\,\delta_s^P/da)_{SI}$	0.0850	0.0700	0.0600	0.0550
	$(d\,\delta_s^P/da)_{SII}$	0.1200	0.1100	0.1000	0.0900
	$(d\,\delta_s^P/da)_u$	0.1500	0.1400	0.1300	0.1200
40CrNiMoA	$(d\,\delta_s^P/da)_s$	0.0775	0.0550	0.0530	0.0530
	$(d\,\delta_s^P/da)_u$	0.1150	0.0780	0.0710	0.0710

In order to prove the crack of the specimen is initiated under the action of P_{10}, two specimens were tested. The tests were interrupted at loads P_1 and P_2 which are less than and greater than P_{10} with the slopes of the secants less than the initial tangent slope by 8.5% and 20% respectively. After the interruption, the specimens were subjected to a second fatigue test. When the crack was extended to a certain degree, the fatigue

test was stopped, and the specimens broken by bending. The microscopic photographs of the cracked flaws are as shown in Fig. 5.

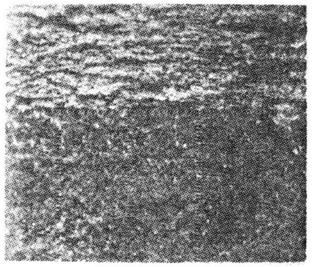


Fig. 5(a)

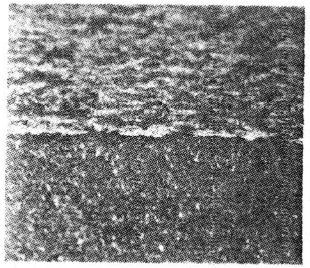


Fig. 5(b)

Fig. 5. Microscopic photographs of the cracked flaws. (a) Specimen No. 4-10-9 acted by load P_1, Δa=0, 50×; (b) Specimen No. 4-10-6, acted by load P_2, Δa=0.02 mm, 50×.

IV. DISCUSSION OF RESULTS

(1) The stress ratios at the crack initiation point obtained by using two methods are in consistant with each other, in which the most relative error is approximately 8%. Under the action of the load P_1 the crack tip was not initiated, and under the action of the load P_2, Δa=0.02 mm (Fig. 5). Therefore it can be recognized that crack is initiated under the action of load P_{10}.

(2) For all plates of various thicknesses the surface crack opening angle is a constant (Table 3) with a scatter of ±8%. Hence, α_I can be recognized to be a fracture-resistant characteristic of these plates at the surface crack initiation.

(3) Before crack initiation, the value of $d\,\delta_s^P/da$ increases with an extension of Δa. After the crack initiation point I, the straight parts of the δ_s^P - Δa curves of the plates of the same thickness are parallel with each other (for example, B=12 mm, Fig. 3, a and Fig. 4, a), i.e. $(d\,\delta_s^P/da)_s$ and $(d\,\delta_s^P/da)_u$ are respectively certain constants (Table 4).

$(d\ \delta_s^P/da)_s$ and $(d\ \delta_s^P/da)_u$ increase with a decrease of plate thickness (Fig. 3, b and Fig. 4, b), which is similar to that of the plane stress fracture toughness K_c of the plates with through cracks. $(d\ \delta_s^P/da)_s$ and $(d\ \delta_s^P/da)_u$ are respectively fracture-resistant characteristics during surface crack stable growth and unstable propagation of these steel plates of various thicknesses. For 40CrNiMoA steel plates of both thicknesses B=12 and 14 mm, $(d\ \delta_s^P/da)_s$ is a constant, $(d\ \delta_s^P/da)_u$ is also a constant (Fig. 4, b and Table 4). $(d\ \delta_s^P/da)_s$ and $(d\ \delta_s^P/da)_u$ can be considered as the fracture-resistant characteristics during crack stable and unstable propagation of the material.

(4) During crack stable growth, 18CrNiWA has a transformation point T, and 40CrNiMoA has not. These may be ascribed to the difference between ultimate strength σ_b and yielding strength $\sigma_{0.2}$, $(\sigma_b-\sigma_{0.2})$, where the former is greater than that of the latter and the path from the tangential point A_1 of P -δ curve with the initial tangent OA_1 to the starting point of horizontal part of the curve of the former is longer than that of the latter. The stress ratio at the transformation point T

$$\sigma_N/\sigma_{0.2}=P_T/(BW - \frac{\pi ac}{2})\sigma_{0.2}\doteq P_T/(BW - \frac{\pi}{2}\frac{B}{2}\frac{W}{8})\sigma_{0.2}=P_T/0.95\sigma_{0.2}BW\doteq 1.$$

(5) For these two types of steel plates, the ratio of the load at the crack unstable propagation starting point U (i.e. the starting point of the rapid propagation) to the maximum load is 0.97-1.0. The propagation after the point U may be designated as The engineering unstable propagation.

V. CONCLUSIONS

(1) Surface crack opening angle α_I is a fracture-resistant characteristic at surface crack initiation of medium strength-high toughness steel plates.

(2) Surface crack plastic opening angle $(d\ \delta_s^P/da)_s$ and $(d\ \delta_s^P/da)_u$ are respectively fracture-resistant characteristics during surface crack stable and unstable propagation of these steel plates of various thicknesses.

(3) When the plate thickness increased to a certain value, $(d\ \delta_s^P/da)_s$ and $(d\ \delta_s^P/da)_u$ reached certain limits respectively, which were unaffected by further increase of plate thickness. Therefore, $(d\ \delta_s^P/da)_s$ and $(d\ \delta_s^P/da)_u$ may considered as fracture-resistant characteristics of material during of a stable and unstable propagation surface crack.

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