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KINETICS OF FATIGUE CRACK PROPAGATION IN STEELS, Ti AND Ni ALLOYS

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In recent years the discrete character of the fracture process has been found to exist in many cases of applied loads. Based on this conception of discreteness, a new method of determining a strength criterion is founded [1]. The skipping process of a crack is clearly seen in cases of fatigue [2, 3]. It has been shown that the crack propagation rate changes at certain values of stress intensity factor [4].

The study based on the discreteness conception predicts that the activation energy and also the size of activation volume change inevitably from a certain level to another when the stress intensity factor reaches a critical value [1].

By analyzing the process of fatigue crack propagation it is possible to estimate the values at which activation energy and stress intensity factor change from a stable stage to accelerating one. Yokobori et al [5] show for aluminum alloy 2024-T3 that there exists a certain value of stress intensity factor range ΔK for which the increase rate of activation energy against decrease of ΔK changes suddenly.

Ivanova and Maslov [1] propose an equation for a spectrum of critical lengths of crack based on the conception that the energy used for a unit length of crack should be constant, as follows:

$$a_{N-1}/a_N = \Delta^{1/n} \tag{1}$$

where

Δ - material constant for fracture, 0,11 for steel, 0,12 for titanium alloy, 0,13 for nickel alloy,

a_{N-1} and a_N - previous and subsequent values of crack length,

n - 1, 2, 4, 8 ... .

When the crack reaches a critical length, plastic instability breaks out at the crack tip [1]. The spectrum of critical values of stress intensity factor K can also be calculated by using the following equation:

$$K_I^{N-1}/K_I^N = \Delta^{1/n} , \tag{2}$$

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where

K_I^{N-1} and K_I^N - previous and subsequent critical values of stress intensity factor.

For calculations using equation (2) it is necessary to know one of the critical values of K_I. By fatigue test data, the second critical value K_I^{II} or fracture toughness for fatigue K_{IC}^S is determined as follows [1]:

$$K_I^{II} = K_{IC}^S = \sigma_e \sqrt{\pi \cdot a_s} \qquad (3)$$

where

σ_e - fatigue limit,

a_s - critical length of stable crack.

In this paper the kinetics of fatigue crack propagation rate is studied and the existence of a correlation between crack size, its propagation rate, stress intensity factor and activation energy is confirmed. The materials used are mild steel STALI 35, chromium Steel 1 x 13, titanium alloy (6,5% Al, 3,5% Mo) and nickel alloy. Table 1a and 1b show the mechanical properties and chemical compositions of materials. Cylindrical specimens, the diameters of which were 7 mm were tested under rotating bending. The crack length and propagation rate are estimated from the increase of the deflection of a specimen during test, using a method developed by authors [6]. The stress intensity factor range for a circular section are calculated from the equation which was originally developed for a square section as follows,

$$\Delta K = Y \cdot \Delta\sigma \sqrt{\pi a} \qquad (4)$$

where

$Y(a/w)$ = correction factor for limited width

$= 1,12 - 0,23\ a/w + 10,55\ (a/w)^2 - 21,72\ (a/w)^3 + 30,39\ (a/w)^4$

W - 0,9 D , D - diameter of specimen.

Figures 1a, 1b, 1c, and 1d show the crack propagation rate against stress intensity factor. The figures show that it is rather reasonable to apply the Paris' law [7] for divided zones of ΔK by a folded line than for the whole region of ΔK by one straight line. That is to say, crack propagation rates for four materials have two or three critical values of ΔK in the process of crack growth, and at the arrival of ΔK at these critical values the crack propagation mode changes from one manner to another. For a titanium alloy, Figure 1c, many experimental data as a whole show two critical values of ΔK, that is to say ΔK - 35,8 and 58,95 MPa•m$^{1/2}$. For Steel 1 x 13, Figure 1a, three critical values are seen, that is to say ΔK - 35,8, 66,84, 107,66 MPa•m$^{1/2}$. For steel STALI 35, Figure 1b, ΔK - 8,97, 15,12, 19,99 MPa•m$^{1/2}$. For nickel alloy, Figure 1d, ΔK - 41,0, 61,5, 84,59 MPa•m$^{1/2}$. Generally the acceleration of crack propagation rate decreases with an increase in ΔK.

In this relation, the change of crack propagation rate da/dN against crack length a are examined. See Figure 2a, 2b, 2c and 2d. The figures show that the manner of increase in da/dN changes some times in the process of crack proceeding.

For the titanium alloy, Figure 2c, these changes take place at a_c - 0,8; 2,3; 3,9; 5,1.10^{-3} m. The ratio of consecutive pairs of a_c values become 0,35; 0,59; 0,77 respectively. These ratios have good agreement with a calculated spectrum of crack lengths for the titanium alloy [8]. The spectrums of crack length are calculated also for other materials. They are shown in Figure 2 by vertical dotted broken lines. Experiments and calculations show good correlation.

For calculation of the K value spectrum, the second critical value K_I^{II} is calculated by equation (3), and then the whole spectrum is calculated by equation (2). For the titanium alloy, for example, it goes such

$$K_I^I = 7,69\ \text{MPa}\cdot\text{m}^{1/2} \leftarrow K_I^{II} = 35,12\ \text{MPa}\cdot\text{m}^{1/2} \rightarrow K_I^{III} = 45,62\ \text{MPa}\cdot\text{m}^{1/2} \rightarrow \ldots$$

$$K_I^{max} = 58,95\ \text{MPa}\cdot\text{m}^{1/2} .$$

In Figure 1c, the calculated critical values of K_I^{II} and K_I^{max} correspond to experimental values of ΔK at which the manner of increase in da/dN changes. It seems that these critical values indicate the stages of fracture process. Figures 1a, 1b and 1d also show the same manner of coincidence with calculated K_I values and experimental ΔK values. Experiments do not show clear signs for intermediate values. It is possible, however, to say that the following relation exists for critical values of ΔK.

$$\Delta K^{N-1}/\Delta K^N = \Delta^{1/n} . \qquad (5)$$

In order to know the change of activation energy for steel STALI 35, experiments are conducted for four temperature levels, T - 293,423,573 and 723° K.

The activation energy can be calculated from the following formula,

$$Q_a = \frac{R\{(\ell n\ da/dN)_{T=T_1} - (\ell n\ da/dN)_{T=T_2}\}}{1/T_2 - 1/T_1} \qquad (6)$$

where

da/dN - crack propagation rate,

T_1, T_2 - absolute temperature,

R - gas constant

Figure 3 shows experimental results of da/dN against 1/T for several values of ΔK for STALI 35. Figure 3 is constructed for an early stage of crack propagation, that is to say, for a ΔK value from 11,53 till 17,94 MPa•m$^{1/2}$. See Figure 4. Figure 5 shows Q_a against ΔK calculated from equation (6). As is seen in the figure, Q_a changes from 191,04 to 71,64 J/mol.

Now let's examine Figure 2b. This figure shows the relation between da/dN and a. From the figure, the relation between $\ell n(da/dN)$ and a is linear for a range of a from 3 to 9.10^{-4}m and this crack length corresponds to ΔK from 8,69 to 15,07 $MPa \cdot m^{1/2}$. Figure 5 shows that Q_a decreases monotonously with increasing ΔK until $\Delta K = 15{,}38$ $MPa \cdot m^{1/2}$, after this value the character of decrease of Q_a changes. Considering that the stage of crack propagation rate changes at about ΔK - 15,38 $MPa \cdot m^{1/2}$ it is possible to say that the change of activation energy is correlated with change of crack propagation rate.

CONCLUSION

1. It is shown that the fatigue cracks propagate according to a discrete character of fracture as follows

$$a_{N-1}/a_N = \Delta^{1/n} .$$

2. The manner of change in crack propagation rate changes several times at critical values of ΔK, and these ΔK values form the following spectrum:

$$\Delta K^{N-1}/\Delta K^N = \Delta^{1/n} .$$

3. It is shown that the change of activation energy corresponds to the stage of fracture process. All stages of the fracture process are considered to be realized in fatigue crack propagation process.

4. It is shown that the crack propagation rate, crack length, activation energy, and stress intensity factor are correlated each other in the process of fatigue.

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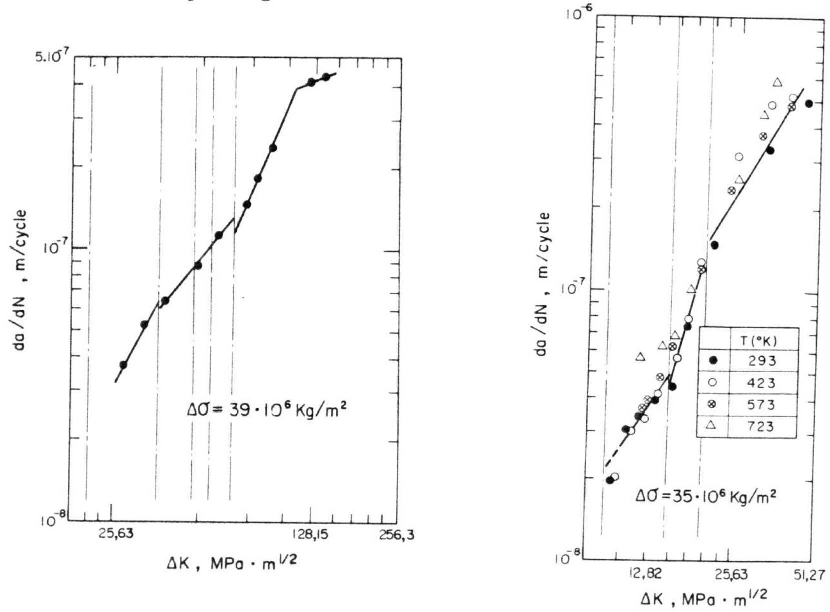
Table 1a Mechanical Properties

Material	σ_B kg/MM^2	$\sigma_{0,2}$ kg/MM^2	δ %	ψ %	a_k kg·M/CM^2
STALI 35	55	32	21	45	6,4
1 x 13	60	42	20	45	7
Ti Alloy	105 - 120	95 - 115	9 - 16	-	3 - 6
Ni Alloy	100	68	13	8 - 16	1 - 3

Table 1b Chemical Compositions

	C	Si	Mn	Cr	Ni	S	P	Mo	Ti	Al	Fe	N
STALI 35	0,35	0,53	0,19	-	-	0,018	0.09	-	-	-	PI*	-
1 x 13	0,15	0,60	0,60	12,0 - 14,0	0,60	less than 0,03	less than 0,03	-	-	-	PI*	-
Ti Alloy	0,02	0,04	-	-	-	-	-	3,0	PI*	6,5	0,04	0,01
Ni Alloy	0,07	0,6	0,6	19 - 22	PI*	-	-	-	2,5 - 2,9	0,6 - 1	-	-

*PI = Principal Ingredient



(a) (b)

Figure 1 Relation Between Crack Propagation Rate and Stress Intensity Factor
(a) Chromium Steel 1 x 13
(b) Mild Steel, STALI 35

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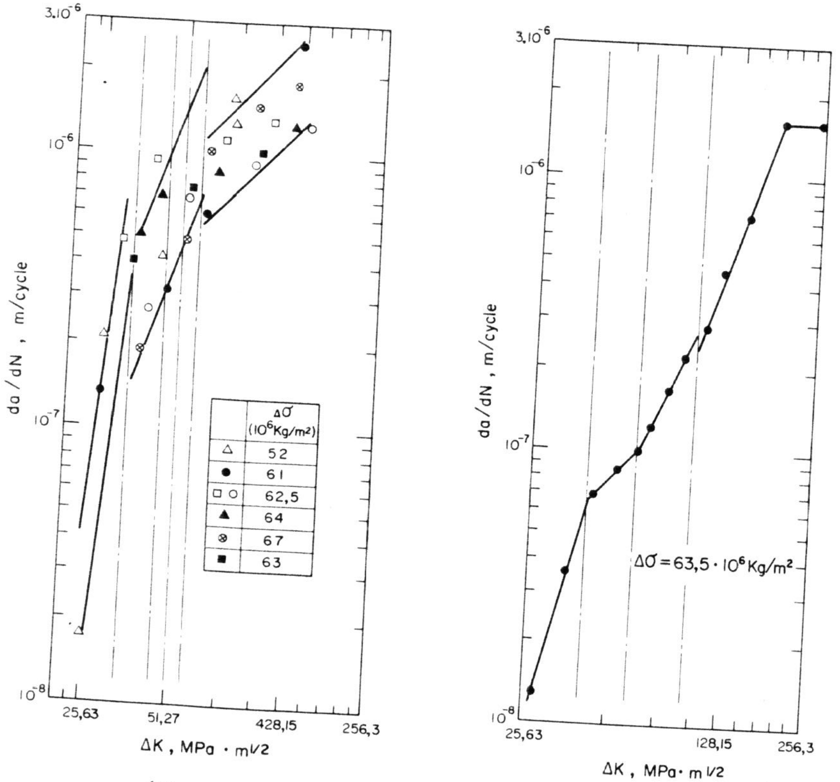
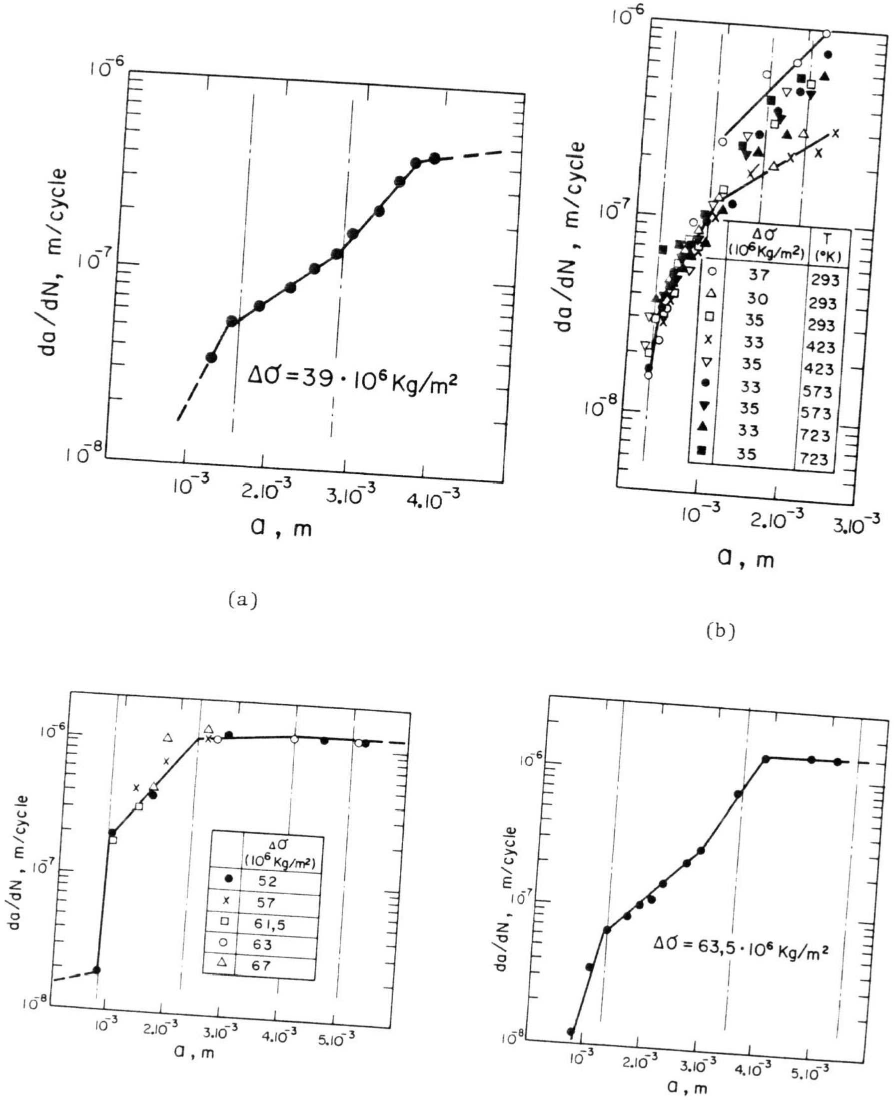


(c) (d)

Figure 1 Relation Between Crack Propagation Rate and Stress Intensity Factor

(c) Titanium Alloy 6,5% Al, 3,5% Mo
(d) Nickel Alloy



(a) (b)

(c) (d)

Figure 2 Relation Between Crack Propagation Rate and Crack Length

(a) Chromium Steel, 1 x 13
(b) Mild Steel, STALI 35
(c) Titanium Alloy 6,5% Al, 3,5% Mo
(d) Nickel Alloy

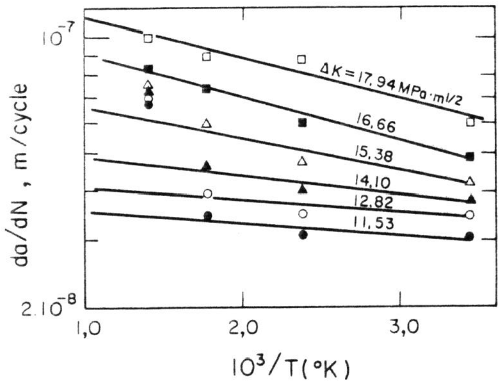


Figure 3 Relation Between Crack Propagation Rate and Test Temperature for Mild Steel STALI 35, $\Delta\sigma = 35.10^6$ kg/m^2

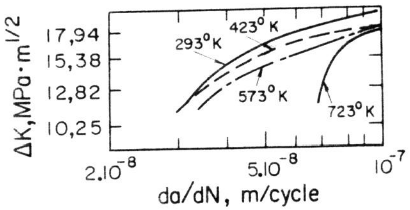


Figure 4 Relation Between Crack Propagation Rate and Stress Intensity Factor for Various Test Temperature for Mild Steel STALI 35

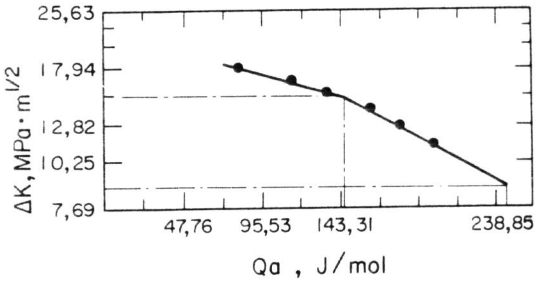


Figure 5 Relation Between Activation Energy and Stress Intensity Factor for Mild Steel STALI 35