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MODELLING OF SHORT CRACK GROWTH IN A LOW-CARBON STEEL SUBJECTED TO ROTATION-BENDING FATIGUE, II. MATHEMATICAL DESCRIPTION

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ABSTRACT

Short crack experiments are carried out on a table model fatigue-machine under rotation-bending fatigue in a rolled low-carbon, low alloyed Bulgarian standard 09Г2 steel (RLCLAS) used for off-shore application.

The experiments include replica monitoring of short crack surface-growth on smooth hour-glass specimens subjected to different symmetric cycling loading, and length measuring of propagating cracks.

A model proposed for description of short fatigue-crack growth-rate at rotation-bending comprises parabolic-linear presentation of the different regimes of fatigue crack propagation, and analytical determination of substantial microstructural barriers at which cracks are slowing down and practically stop. A comparison is made between the rotation-bending and previously investigated pull-pull fatigue behaviour of RLCLAS 09Г2.

Key words: Rotation-bending fatigue, Short fatigue crack growth, Crack growth rate, Fatigue modelling

INTRODUCTION

Fatigue data obtained by the Method of Short Fatigue Crack Growth investigations are modelled using a system of parabolic-linear functions. The crack behaviour is described and presented in three different stages bordered by microstructural barriers which have substantial impact on fatigue process [1, 2].

During the first stage called *Stage of short fatigue crack growth (SFC) f*atigue cracks initiate and propagate as shear cracks – MODE II. Entering into the second stage known as *Stage of physically small fatigue crack growth (PhSFC)* the shear fatigue cracks change into tensile cracks – MODE I. During these two stages fatigue cracks are strongly influenced by different elements of metal microstructure, and their propagation can be described by parabolic functions.

The third stage, Stage *of long fatigue crack growth (LFC),* shows that metal microstructure does not influence fatigue crack growth and fatigue crack propagates with increasing rate up to the complete failure of specimen. The modelling of this stage uses linear function.

EXPERIMENTAL

Experiments are carried out on a new table-model fatigue machine for rotation-bending FATROBEM–2004 that is designed, constructed and assembled in the Laboratory of Plastic Deformation of the University of Chemical Technology and Metallurgy-Sofia [3, 4]. The material tested is a rolled low-carbon, low alloyed Bulgarian standard 09Г2 steel (RLCLAS) used for off-shore application. RLCLAS 09Г2 has chemical composition and mechanical properties described in [3] and average grain size d = 25,6μm. The specimens are of smooth hour-glass type with a surface properly polished according to the corresponding technical standards. A replica method is used for monitoring the specimen surface state and initiated crack growth at fixed intervals of the applied cycling loading.

The experiments are conducted in air under symmetric Rotation-Bending (R-B) fatigue, R = -1, at different cyclic frequency and loading conditions, Table 1. The data obtained are compared to those from asymmetric Pull-Pull (P-P) fatigue tests (R = 0,1) carried out in air, Table 2, [2].

Table 1. Experimental conditions at R-B

Specimen number	Stress range Δσ, MPa	Frequency f, Hz
1	620	11
2	620	11
3	580	11
4	620	6,6

Table 2. Experimental conditions at P-P

Specimen number	Stress range Δσ, MPa	Frequency f, Hz
1	387	190
2	396	190
3	405	190

RESULTS AND DISCUSSION

Crack growth rate *da/dN*, μm/cycle (1) is determined as a ratio of divided differences between two concessive values of *a*, μm and *N*, cycles:

$$\left(\frac{da}{dN}\right)_{n+1} = \frac{a_{n+1} - a_n}{N_{n+1} - N_n} \qquad (1)$$

An algorithm for determining the values of the substantial microstructural barriers d_1 and d_2 is used to all data obtained from the tests. The parameters d_1 and d_2 represent the borders between the stages SFC, PhSFC and LFC. The algorithm consists of the following:

– considering all successive points from "Crack growth rate *da/dN* – crack length *a*" presentation, for which is valid (2)

$$\left(\frac{da}{dN}\right)_{n+1} < \left(\frac{da}{dN}\right)_{n}, \qquad (2)$$

and plotting a linear function (3) (in log-log scale) using the least square method:

$$\frac{da}{dN} = Da + E \text{ , where D, E are the line coefficients;} \tag{3}$$

– obtaining the values of d_{1i} and d_{2i} parameters, corresponding to crack lengths at which a crack stops its propagation, (4):

$$\frac{da}{dN} = 0 \tag{4}$$

– finding the average values d_1 and d_2 of all obtained values d_{1i} and d_{2i}, where d_1 is the border between the stages SFC, PhSFC and d_2 – between the stages PhSFC, LFC.

The values of the parameters d_{1i} and d_{2i} are shown in Table 3 and their corresponding average values d_1 and d_2 presented in Table 4.

Table 3. Values of parameters d_1 and d_2

Rotation-Bending							
Specimen 1		Specimen 2		Specimen 3		Specimen 4	
d_1	d_2	d_1	d_2	d_1	d_2	d_1	d_2
233; 277	515	-	371	190 254	544; 794 791; 608 565	222; 207 210	335

Table 4. Average values of parameters d_1 and d_2

Rotation-Bending		Pull-pull	
d_1, μm	d_2, μm	d_1, μm	d_2, μm
230	565	65	156

To describe the fatigue behaviour during the different stages of crack growth, we propose the following mathematical model (5)-(7) in log-log scale [2]:

$$\text{I}^{\text{-st}} \text{ stage (SFC):} \quad \frac{da}{dN} = A_1 a^2 + B_1 a + C_1 \quad a \in (a_0 , d_1] \tag{5}$$

$$\text{II}^{\text{-nd}} \text{ stage (PhSFC)} \quad \frac{da}{dN} = A_2 a^2 + B_2 a + C_2 \quad a \in [d_1 , d_2] \tag{6}$$

$$\text{III}^{\text{-th}} \text{ stage (LFC):} \quad \frac{da}{dN} = A_3 a^{B_3} \quad a \in [d_2 , a_f), \tag{7}$$

where a_0, μm is the initial crack length and a_f , μm – the final crack length at failure. The values of all coefficients A, B and C in equations (5) – (7) are determined by using the least-square method and shown in Table 5.

The experimental data described mathematically by the proposed model fit well to a parabolic-linear dependence "Crack growth rate, *da/dN* – crack length *a*" and are presented in Fig. 1 (for R-B) and Fig. 2 (for P-P). Both sets of curves in Fig. 1 and Fig. 2 are shown together in Fig. 3 for a comparative analysis. The mathematical model is applied only to the main cracks; it is important to mark, because some specimens have more than one crack.

Table 5.Values of coefficients A, B and C

Rotation-Bending								
Spec. No	SFC			PhSFC			LFC	
	$A_1.10^{-5}$	B_1	C_1	$A_2.10^{-5}$	B_2	C_2	$A_3.10^{-5}$	B_3
1	-0.400	0.00140	-0.0951	-0.040	0.00030	-0.0507	0.002	2.0082
2	-0.020	0.00020	-0.0130	-0.060	0.00050	-0.0884	0.080	1.5403
3	-0.020	0.00006	-0.0011	-0.040	0.00030	-0.0520	0.040	1.5987
4	0.010	- 0.0001	0.0206	-0.100	0.00080	-0.1328	0.003	2.0636
Pull-Pull								
Spec. No	SFC			PhSFC			LFC	
	$A_1.10^{-5}$	B_1	C_1	$A_2.10^{-5}$	B_2	C_2	$A_3.10^{-5}$	B_3
1	-	-	-	-	-	-	1.00	1.0229
2	-	-	-	-0.040	0.0001	-0.0047	2.00	0.9919
3	-	-	-	-0.100	0.0002	-0.0105	0.02	1.7178

All Figs. 1-3 clearly show the three stages – two parabolic and one linear – of the dependencies "Crack growth rate, da/dN – crack length a".

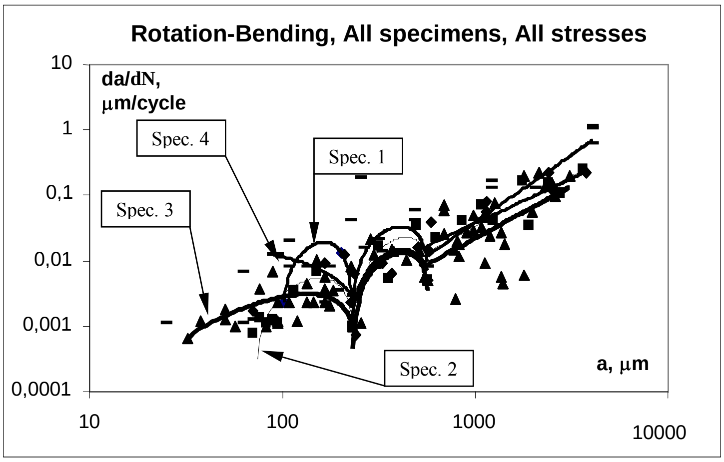

Fig. 1. Dependence "Crack growth rate, da/dN – crack length a"

The values of microstructural barriers dividing fatigue crack growing into three different stages are determined by the proposed algorithm. For R-B loading: d_1=230μm, d_2=565 μm; for P-P: d_1=65μm, d_2=156μm. In Fig. 1 can be seen that during the first stage the highest growth rate belongs to Specimen *1* while during the stages of physically small and long fatigue crack, the highest growth rate is that of Specimen *4*. At the same time the lowest growth rate for all stages and all specimens belongs to the main crack of Specimen *3*.

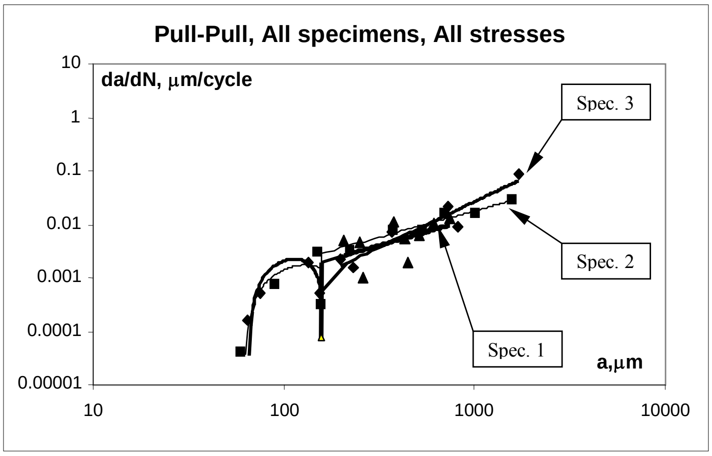

Fig. 2. "Crack growth rate, da/dN – crack length a"

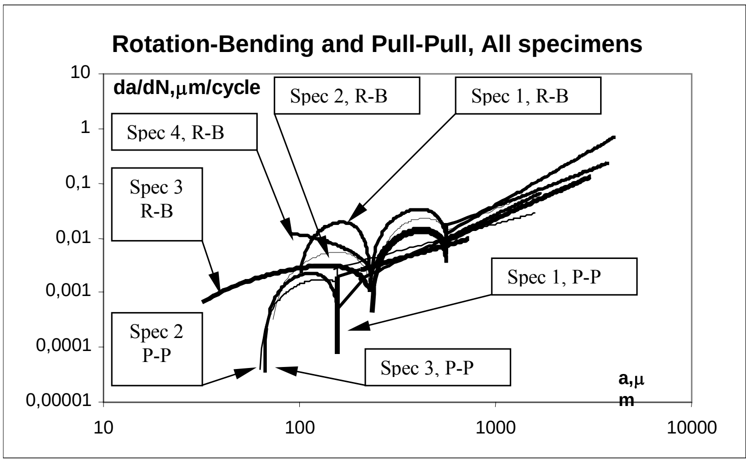

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Fig. 3. *"Crack growth rate, da/dN – crack length a"*

Figs. 2–3 show that the stages for Pull-Pull fatigue [2] are shifted to smaller crack lengths which correspond to smaller values of *d*-parameters comparing to Rotation-Bending loading.

At P-P fatigue the parabolas describing the crack growth in the first two stages are lying below than those belonging to R-B fatigue. This can be explained by the more severe conditions at R-B, characterized with a more unfavourable ratio R = -1. A reason for the greater values of d_1 and d_2 at R-B fatigue can be found in the surface layers of specimens, subjected to the greatest stresses. It causes a predominant surface crack-growth instead of growth in depth. In this context an interesting fact is the coincidence of the following ratios

$$\left(d_1 / d_2\right)_{R-B} = 230 / 565 = 0.407 \text{ and } \left(d_1 / d_2\right)_{P-P} = 65 / 156 = 0.417 , \quad (7)$$

showing that the fatigue crack in RLCLAS 09Г2 stops, in both cases, at the barriers which ratio is a constant, or the ratio between the lengths of SFC and PhSFC stages does not depend on the type of fatigue. Then another ratio

$$(d_2 - d_1)_{R-B} / (d_2 - d_1)_{P-P} = (565 - 230)/(156 - 65) = 3.68 \qquad (8)$$

gives us information about the beginning of LFC stage at R-B fatigue, which starts after a PhSFC stage which is 3.68 times longer than the corresponding one at P-P fatigue. Also it means that under R-B loading, the surface size of physically small fatigue crack is 3.68 times longer than its size at P-P loading. So, when SFC and PhSFC cracks under R-B propagate mainly on surface (R-B PhSFC crack has 3.68 times longer surface length than P-P one), SFC and PhSFC cracks under P-P develop mainly in depth (P-P PhSFC crack probably has 3.68 times greater size in depth than R-B one). Of course, it is true if the effective fracture surfaces in both cases of R-B and P-P fatigue are almost equal at the beginning of LFC stage.

SUMMARY

A model is proposed for description of short crack growth behaviour at Rotation-Bending fatigue based on a similar method developed for Pull-Pull fatigue. The proposed method presents a new more precise analytical determination of substantial microstructural barriers at which short cracks stop.

A comparison made between the characterization parameters and graphical presentations of Pull-Pull fatigue previously investigated in RLCLAS 09Г2 and Rotation-Bending fatigue show some differences between both types of fatigue and improve our understanding of fatigue phenomenon.

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