THE INFLUENCE OF LOAD HISTORY ON FRACTURE TOUGHNESS DATA

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The previously proposed model of unstable fatigue crack growth is used to explain a large (in comparison with other mechanical characteristics) scatter of static fracture toughness for the 15Kh2MFA and 15Kh2NMFA steels at temperatures below the ductile-to-brittle transition temperature. A method is proposed of evaluating the minimum fracture toughness of the material under static loading based on the irregular fatigue crack growth process control in the stage of crack initiation.

INTRODUCTION

One of the reasons having a detrimental effect on the practical application of the linear fracture mechanics approaches for calculating the brittle strength of structural members is a very large scatter with experimental values of the critical stress intensity factor (SIF) under static loading K_{Ic} in comparison with the scatter of the mechanical characteristics obtained on smooth specimens (e.g. yield stress, ultimate stress, relative reduction of the cross - section area, ect.) (Ritchie (1), Mudry (2), McCade (3), Clark (4), Hirano (5)). It is therefore necessary to increase the safety factor, as well as to test a large number of specimens to ensure a high reliability of the data. However, the latter does not guarantee obtaining the minimum K_{Ic} value of the material and the method of the lower envelope is not completely justified for this case (6).

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If the difference in the critical SIF values for the same material obtained in different laboratories is explained by different test methods, specimen geometry, ect., the scatter of the K_{Ic} values obtained on the specimens of the same standard size and with the same testing equipment, is attributed to the fact that the brittle fracture resistance is sensitive to the heterogeneity of the local properties of the material, inclusions, etc. (2, 3).

Currently available standardization documents for determining fracture toughness in plane strain specify the conditions of the fatigue crack initiation (6-9). It is assumed that the conditions of fatigue crack initiation have no effect on the K_{Ic} value if the maximum stress intensity factor of the cycle, K_{max}, in the final stage does not exceed a certain value. In different documents these requirements almost coincide.

On the basis of the investigations performed earlier it has been found that for cyclically softening materials at the temperatures below brittle-to-ductile transition and at high K_{max} values the stable fatigue crack propagation alternates with unstable propagation (brittle crack jumps). The length of the specimen brittle jumps varies from several parts per mm up to several mm. The lowest value of the maximum SIF at which the transition from stable to unstable crack growth occurs is taken as the cyclic fracture toughness K_{fc}. For the materials under consideration the cyclic fracture toughness is appreciably lower (1.5 - 3 times) then the static fracture toughness (Troshchenko et al (10)).

This paper presents an approach to predict the scatter of fracture toughness values, K_{Ic}.

MATERIALS AND EXPERIMENTAL PROCEDURES

The investigations involved cyclically softening materials tested at temperatures below brittle-to-ductile transition for which the cyclic fracture toughness is lower than that under static loading. Fracture toughness characteristics were determined for the 15Kh2MFA and 15Kh2NMFA steels. Mechanical properties of the steels are listed in Table 1.

However, regardless of a relatively strict specifying of the fatigue crack initiation conditions, in practice the values of the critical SIF are greatly scattered (1-5).

TABLE 1 - Mechanical Properties of the Steels Studied

Steel	15Kh2MFA	15Kh2NMFA
Temperature (K)	293	183
0.2% offset yield strength (MPa)	950	750
Ultimate tensile strength (MPa)	1070	840
Relative elongation (%)	16.6	25.0
Relative reduction in area (%)	67.2	67.0
Brittle-to-ductile transition temperature (K)	393	292

The growing of initial cracks and static fracture toughness tests were carried out in plane bending of specimens with a cross - section of 25 x 70 mm on UMP02-04 testing machine and off - center tension of compact specimens on a Hydropuls 400 kN testing machine in accordance with (7).

Figure 1 shows schematically the fracture surface of the cyclically loaded 15Kh2MFA specimen. Light areas correspond to the stable crack growth and dashed ones to unstable crack growth (brittle crack jumps).

The maximum SIF which corresponds to the first (N1) brittle crack jump is taken as the cyclic fracture toughness K_{fc}.

The length of the first crack jump did not exceed 0.1 mm so that it was possible to identify the jump unambiguously on the specimen fracture surface using an optical microscope.

The stress intensity factors for plane specimens in bending and for compact specimens in off-center tension were determined by the well-known equation (7).

The static fracture toughness tests on the 15Kh2MFA and 15Kh2NMFA steels were carried out at 293 and 183 K, respectively. These temperatures are considerably lower than the T_{br}.

EXPERIMENTAL RESULTS

Figure 2 shows the K_{Ic} dependencies on the maximum SIF, K_{fmax}, and the cyclic fracture toughness dependencies on the normalized fatigue crack critical length $\bar{l}_{fc} = l_{fc}/W$ corresponding to the transition form its stable propagation to unstable propagation (here l_{fc} is the critical fatigue crack length) for the 15Kh2MFA steel at 293 K.

Cyclic fracture toughness of the 15Kh2MFA steel is appreciably lower when compared with static fracture toughness (Fig.2). Thus, the mean value of the cyclic fracture toughness K_{fc} of the 15Kh2MFA steel at 293 K is 2 times lower than K_{Ic} at the same test temperature.

Special attention should be given to a appreciable difference in the scatter of the fracture toughness for the steels considered under static and cyclic loading. The scatter band of the critical SIF in static loading, K_{Ic}, is quite wide 41 MPa$\sqrt{m}$ for the 15Kh2MFA steel. The scatter of the cyclic fracture toughness, K_{fc}, is considerably smaller. The $\Delta K_{Ic}/\Delta K_{fc}$ ratio for the 15Kh2MFA is 7.8 and the ratio of the standard deviation is 6.4.

DISCUSSION

We shall try to analyze the reasons for such a large scatter of the fracture toughness data under static loading and the difference in the scatter of the experimental fracture toughness data under static and cyclic loading.

From Fig. 2 it follows that the K_{Ic} value is independent of the K_{fmax} level at the final stage of fatigue precracking. In some cases the static fracture toughness of the specimens with a "sharper" crack, i.e. with lower K_{fmax} value, is higher than the K_{Ic} values obtained on specimens with a more blunt crack, i.e. with a higher K_{fmax}.

One can assume that the larger scatter of the static fracture toughness values of the 15Kh2NMFA steel at 183 K as compared to the cyclic fracture toughness is caused by different types of specimens used in the tests. Static fracture toughness was determined on compact tension specimens while cyclic fracture toughness on plane specimens in bending. However, the results obtained for the 15Kh2MFA steel on the same type of compact specimens also exhibit a similar relationship between the scatter of the static and cyclic fracture toughness data (Fig. 2).

Apparently, the local heterogeneity of the material properties, used generally to explain the large scatter of fracture toughness values, cannot be applied here, since in this case standard deviation for the cyclic fracture toughness should be larger because the transition to the fatigue crack unstable growth under cyclic loading occurs at lower values of $K_{max} = K_{Ic}$ and, therefore, at a smaller plastic zone size at the crack tip than in the case of static loading. Yet this does not agree with the experimental data presented in Fig. 2.

The authors of a number works, e.g. Ostergard et al (11), note that in some steels the growth of a fatigue crack occurs irregulary. We obtained similar results. Figure 3 shows the dependence of the crack extension Δl on the number of load cycles for the 15Kh2MFA steel at T = 293 K obtained on a 25 mm thick compact specimen with an initial crack of length l =16.28 mm no crack growth is observed up to N = 120 cycles, and only at further loading does the crack begin to grow, apparently in each cycle, i.e. continuously. The process of alternation of the crack growth and arrest is repeated many times.

Figure 4,a show one block of the "stable" fatigue crack growth process which is characterized by the following parameters: the magnitude of the constinuous crack extension, Δl_c, the number of load cycles within which the crack is growing continuously, ΔN_c, and the number of cycles of the crack growth delay, ΔN_d.

Under cyclic loading the accumulation of fatigue damage occurs in the vicinity of the crack tip and, accordingly, the embrittlement of the material. Considering the irregular character of the crack growth, the degree of the material embrittlement at a constant ΔK range will change from cycle to cycle both at the stage of the crack growth delay and at the stage of its continuous growth (Fig. 4,a). Considering this circumstance, one should expect that in K_{Ic} testing different degress of the material embrittlement at the crack tip in the fanal stage of its initiation would lead to different fracture toughness values under static loading. The existing standardization documents for static fracture toughness testing (6-9) when considering the growing of a fatigue precrack impose limitations only on the magnitude of the crack extension, the maximum SIF, K_{fmax} , and the number of load cycles at the final stage of the crack initiation, but the process of irregular crack growth is not controlled. Therefore, the scatter of the static fracture toughness values can be largely stipulated by different degress of the material embrittlement at the crack tip occuring at the stage of crack initiation in different specimens.

To verify the above assumption static fracture toughness tests were performed on 19 mm thick compact tension specimens of the 15Kh2MFA steel at 293 K. Initial cracks were grown in accordance with (8) but at the final stage of initiation the process of the irregular crack growth was under control and cyclic loading was stopped at a different number of cycles at the stage of delay, $\Delta N'_d$, and continuous crack growth, $\Delta N'_c$, (Fig. 4,a) following the recommendations proposed in (11). In this case the maximum SIF, K_{fmax} , value at the final stage of crack initiation (with the irregular fatigue crack growth process being under control) was within 25 - 28 MPa$\sqrt{m}$. Figure 4,b presents the static fracture toughness dependence on the number of load cycles, $\Delta N'_d$, at the stage of the crack growth delay and Fig. 4,c shows the K_{Ic} dependence in the number of load cycles at the stage of continuous crack growth, $\Delta N'_c$.

From Figs. 5(b) and (c) it follows that for the 15Kh2MFA steel, with an increase in the number of load cycles at the stage of the crack growth delay static fracture toughness decreases while at the stage of the continuous fatigue crack growth the K_{Ic} value increases.

Of great importance is the problem of the minimum SIF range from which cycle loading at the stage of fatigue precracking will affect the K_{Ic} value, i.e. that which will induce the material embrittlement in the damage zone at the crack tip.

The investigations performed earlier (12) revealed that for the 15Kh2MFA steel at 293 K the embrittlement of the material in the damage zone at the crack tip under cyclic loading occurs at the SIF range values close to the threshold ΔK_{th}.

Thus in the absence of control of the irregular crack growth at the final stage of the fatigue crack initiation, the fracture toughness of the specimen with a "sharper" crack, e.g. at $K_{fmax} = K_{th}$, may be higher than that of the specimen with a crack grown at $K_{fmax} >> K_{th}$.

The above fact is valid only when the cyclic mode of loading reduces the fracture toughness, i.e. when $K_{fc} < K_{Ic}$. At $K_{fc} = K_{Ic}$ the cyclic mode of loading at the stage of fatigue precracking will not cause material embrittlement in the damage zone and, consequently, will not affect the K_{Ic} value. In this case the scatter of the static fracture toughness should be minimal and will be related only to the local scatter of the material properties.

On the basis of the generalization of the data obtained it is possible to propose a method for determining the minimum static fracture toughness from the results of testing a single specimen. In this case the irregular crack growth at the final stage of its initiation is controlled. Cyclic loading is stopped at the points of transition from the stage of the crack delay to its continuous growth (point 2 in Fig. 4,a). Then the specimen is subjected to fracture toughness testing under static loading in accordance with (6-9).

SYMBOLS USED

K_{Ic} = fracture toughness under static loading (MPa$\sqrt{m}$)

K_{fc} = fracture toughness under cyclic losding (MPa$\sqrt{m}$)

K_{min} = minimal SIF in a load cycle (MPa$\sqrt{m}$)

K_{max} = maximal SIF in a load cycle

ΔK = the SIF range

K_{th} = threshold SIF

l = crack length

SIF = stress intensity factor

σ_y = 0.2% offset yield stress

REFERENCES

(1) Ritchie, R., Server, W. and Wullaert, R., Metal. Trans. 10A, 1979, pp. 1557-1573.

(2) Mudry, F., Proc. 4th Advance Seminar on Elastic-Plastic Fracture Mechanics, Dordrecht, 1985, pp. 303-323.

(3) McCabe, D., J. Test. Eval. 8, 1980, pp. 306-313.

(4) Clark, G., J. Test. Eval. 8, 1980, pp. 213-220.

(5) Hirano, K., Kobayashi, H. and Nakazava, H., J. Test. Eval. 13, 1985, pp. 356-362.

(6) 3.71, British Standards Institution Draft for Development, 1972, London.

(7) ASTM E399-83, Annual Book of ASTM Standards, 1985.

(8) GOST 25.506 - 85, Izdatelstvo Standartov, 1985, Moscow.

(9) ASTM E399-74, Annual Book of ASTM Standards. 1976.

(10) Troshchenko, V., Pokrovsky, V. and Prokopenko, A., Fatig. Eng. Mater. and Struct. 1, 1979, pp. 247-266.

(11) Ostergard, D., Thomas, I. and Hillberry, B., Fatigue Crack Growth Meas. and Data Anal., Philadelphia, 1981, pp. 194-203.

(12) Troshchenko, V.; Yasniy, P. and Pokrovsky, V., Probl. Prochn., N.11, 1985, pp. 30-35.

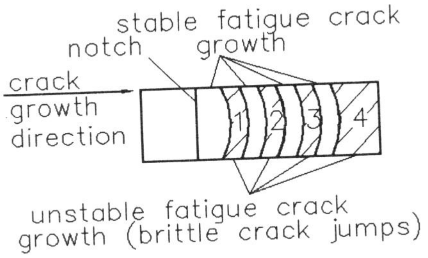

Fig.1 The surface of the specimen fractured under cyclic loading.

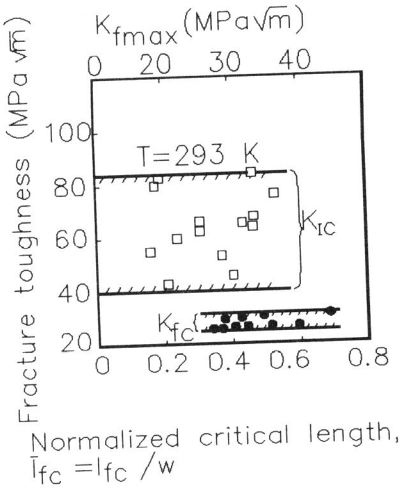

Fig.2. K_{IC} versus K_{fmax} and K_{fc} versus $\bar{l}_{fc}$ dependences.

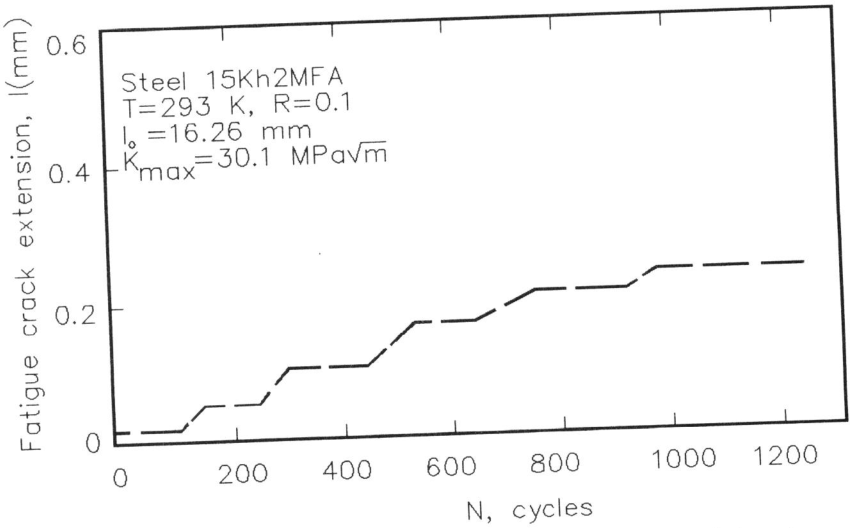

Fig.3 Fatigue crack extension vs the number of load cycles.

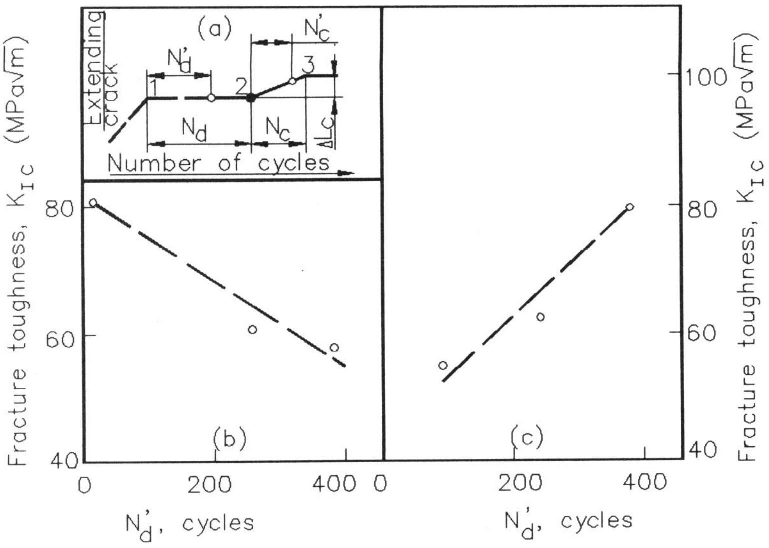

Fig.4 Single block of the fatigue crack irregular growth.