INFLUENCE OF PRELIMINARY PLASTIC DEFORMATION OF CRACK RESISTANCE

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ABSTRACT

The influence of preliminary cyclic plastic deformation by tension-compression ($R_\varepsilon=\varepsilon_{min}/\varepsilon_{max}=-1$) on the fracture toughnes by static and cyclic loading of 15Kh2MFA heat resistant steel in two conditions was investigated.

Unnotched plates (gage length cross section 12,5x45 and 14x45 mm) were subjected to preliminary cyclic plastic deformation and one edge notched specimens were done from them after deformation. The compact specimens were made from failed plates too (gage length cross section 12.5x45.0 mm).

The amplitude of the elastoplastic deformation was 0.3, 0.45 and 0.7% and the relative number of cyclics $\bar{N}$= 0.3, 0.6 and 0.85 ($\bar{N}$=N/Nc, where Nc is the number of load cycles until the appearance of a crack with a length of 0.5-1.0 mm on the surface).

It was established that in the case of relatively small preliminary deformation the change in static fracture toughness is caused by a change in yield strength as the result of the Bauschinger effect. However, with an increase in cyclic deformation the total irreversibly dispersed specific energy of inelastic deformation and the structural changes in the material are the determining factor. A physically based method is proposed for prediction of the influence of preliminary cyclic plastic deformation on the static and cyclic fracture toughness of cyclically softening steels.

KEYWORDS

Fracture toughness, preliminary plastic deformation, static loads, cyclic loads, crack resistance, stress intensity factor.

INTRODUCTION

While operating some elements of highly loaded structures (such as in a zone of stress concentration) may be subjected to cyclic inelastic deformation, which leads to a change in mechanical properties of the material.

Together with the influence on the characteristics of strength and plasticity (Ivanova and Terent'ev, 1977; Lebedev at al., 1978) of preliminary cyclic plastic deformation the latter also has a substantial influence on the fracture toughness by static loading K_{1c} (Ivanova et al., 1966; Kanadzava, 1968; Troshchenko et al., 1987).

Although in the majority of cases preliminary cyclic plastic deformation reduces K_{1c} , in general, its influence on the above characteristic is ambiguous and will apparently be determined by the conditions (hard or soft) and amplitude of loading, the ratio of the temperatures of preliminary cyclic plastic deformation and testing, and the type of material.

In this work the influence of preliminary cyclic plastic deformation on the characteristics of fracture toughness of a heat-resistant steel under static and cyclic loads was studied.

EXPERIMENTAL PROCEDURE AND MATERIALS

The chemical compositions of the steel, wt. %, was as follows: 0.18C; 0.27Si; 0.47Mn; 2.58 Cr; 0.16Ni; 0.62 Mo; 0.3V; 0.019S; 0.013P; 0.011Ti. The characteristics of the mechanical properties of the tested steels in two condition are presented in Table.

Table. Characteristics of the mechanical properties of tested steels at 293 °K.

Steels	σ_y, MPa	σ_u, MPa	δ, %	ψ, %
15Kh2MFA(I)	584	700	21.0	74.6
15Kh2MFA(II)	1100	1157	16.6	67.2

The characteristics of fracture toughness under static $K_{1c}(K_c)$ and cyclic K^{l}_{fc} and K^{k}_{fc} loads was investigated in uniaxial tension of plates with thicknesses of t=12.5 and 14 mm with an edge notch and also of compact specimens with a thickness of t=12.5 mm at temperatures of 123 and 293 K, where K^{l}_{fc} and K^{k}_{fc} are the critical stress intensity factors corresponding to the minimum cyclic and dynamic fracture toughnesses (Troshchenko et al., 1987).

Unnotched plates (gage length cross section 12.5x45 and 14x24 mm) were subjected to preliminary cyclic plastic deformation and one edge notched specimens were done from them after deformation. The compact specimens were made from failed plates (gage length cross section 12,5x45 mm). In this case only those failed plates, in testing of which the level of net stresses did not exceed $0,4\sigma_y$ (σ_y is the nominal yield strength of the steel), were used. The preliminary cyclic plastic deformation was done with hard (ε_a = const) elastoplastic loading and with a stress ratio of the loading cycle of $R_\varepsilon = \varepsilon_{min}/\varepsilon_{max} = -1$, where ε_a , ε_{min} and ε_{max} are the amplitude, minimum, and maximum elastoplastic deformation of the loading cycle. The amplitude of the elastoplastic deformation was 0.3, 0.45 and 0.7% and the relative number of cycles $\bar{N}$=0.3, 0.6 and 0.85 ($\bar{N} = N/N_c$), where N_c is the number of load cycles until the appearance of a crack with a length of 0.5-1.0 mm on the surface).

The fracture toughness in static loading was determined in accordance with the methods (GOST 25.506-85). The critical stress intensity factors K^{l}_{fc} and K^{k}_{fc} were determined with a stress ratio of $R=K_{min}/K_{max}=0.1$ (K_{min} and K_{max} are the minimum and maximum stress intensity factors).

The influence of preliminary cyclic plastic deformation on the fracture toughness of 15Kh2MFA steel in the plastic (I) and embrittled (II) conditions was investigated.

The preliminary cyclic plastic deformation of the specimens of 15Kh2MFA(I) and 15Kh2MFA(II) steel was done at 293 K. In the first case the specimens were fractured at 123 K and in the second at room temperature. The ductile crack growth in determination of static fracture toughness was not absent.

EXPERIMENTAL RESULTS AND DISCUSSION

The character of the influence of preliminary cyclic plastic deformation on the fracture toughness of the investigated steel under static and cyclic loads is quite complex (Fig.1). An increase in the relative number of cycles $\bar{N}$ to 0.3 decreases the static and cyclic fracture toughness of 15Kh2MFA(I) steel at 123 K, but with $\bar{N}$>0.3 the fracture toughness at static loading increases, although there is practically no change in K^{l}_{fc} and K^{k}_{fc}. While with $\bar{N}$=0.3 an increase in the amplitude of elastoplastic deformation ε_a reduces K_{1c}, with the maximum number of cycles ($\bar{N}$=0.85) the

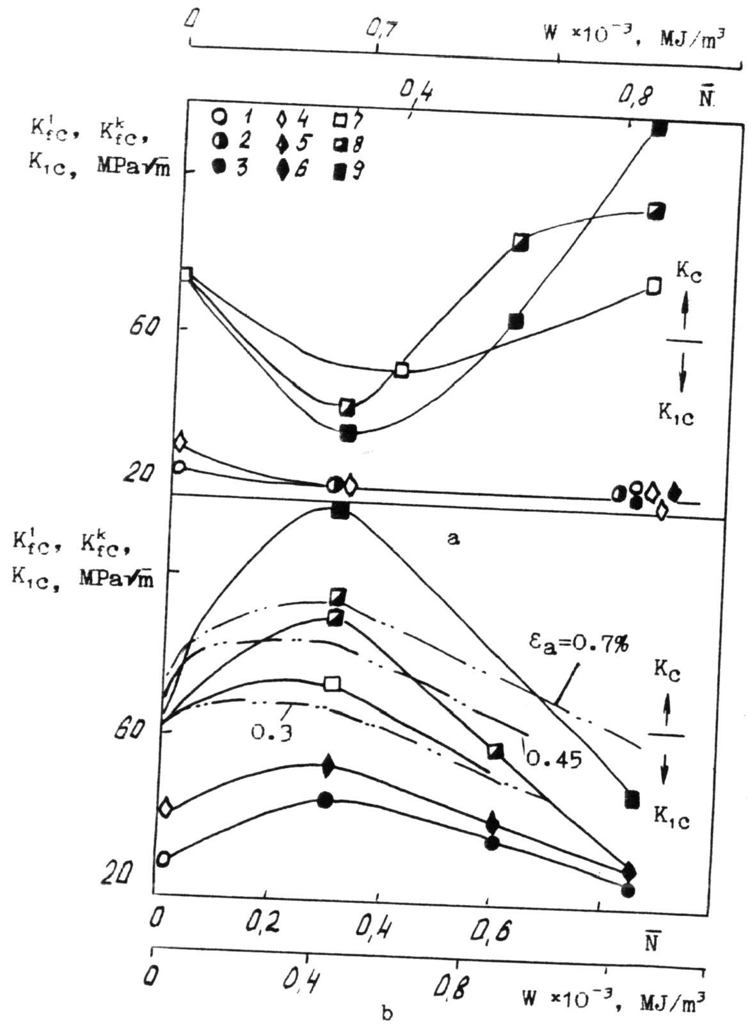

Fig.1. Experimental (solid lines) and calculated · (broken lines) relationships of the critical stress intensity factor K^1_{fc} (1-3), K^k_{fc} (4-6), and $K_{1c}(K_c)$ (7-9) of 15Kh2MFA(I)steel at 123 K (a) and of 15Kh2MFA(II) steel at 293 K (b) to the number of cycles $\bar{N}$ and the specfic energy of inelastic deformation W:(1,4,7) $\varepsilon_a=0.3\%$; (2,5,8) $\varepsilon_a=0.45\%$; (3,6,9) $\varepsilon_a= 0.7\%$.

critical stress intensity factor K_c increases.

Fig. 1 shows the boundaries (horizontal short lines) of fulfillment of conditions of plane strain (maximum constraint of plastic deformations at the crack tip) according to the criterion $t > 2.5(K_{1c}/ \sigma_y)^2$.

The influence of preliminary cyclic plastic deformation on fracture toughness may be described through the specific energy of plastic deformation W (Fig.1), which was determined as follows (Troshchenko, 1966):

$$W = [\Delta W - \Delta W_r (\Delta W / \Delta W_r)^{\beta} N, \qquad (1)$$

where $\Delta \underline{W}$ is the energy density of inelastic deformation per cycle ($\bar{N}$=0.5); ΔWr is the density energy of inelastic deformation per cycle with stresses equal to the fatigue limit; β is a parameter which defines the intensity of the increment in the nondangerous portion of the dissipated energy with an increase of stress amplitude.

At the same time taking into consideration the influence of temperature and loading rate on K_{1c} and σ_y and summarizing a multitude of experimental data for steels, it was established (Hahn et al., 1971) that

$$K_{1c} = (1 / \sigma_y)^2 (\sigma_c / 7.431)^3 \qquad (2)$$

where σ_c - cleavage stress.

With the use of Eq. (2) let us analyze the influence of preliminary cyclic plastic deformation (R_ε =-1) on the brittle fracture resistance of 15Kh2MFA(I) and 15Kh2MFA(II) steels.

For 15Kh2MFA (II) steel (Fig.1) the increase in brittle fracture resistance with an increase in the number of cycles of $\bar{N} < 0.3$ is related to the Bauschinger effect. At the same time the greatest reduction in yield strength σ_y is found in the course of several loading cycles and stabilization of it occurs at approximately $\bar{N}$=0.1. During cyclic loading with $\bar{N} < 0.1$ the change σ_c may be neglected since the fatigue damage is negligible and plastic deformation is absent.

According to Eq.(2) a decrease in σ_y with σ_c= const must lead to an increase in fracture toughness K_{1c}. The reduction static fracture foughness of 15Kh2MFA(II) steel with a further increase in the number of cycles ($\bar{N} > 0.3$) (Fig.1) occurs with an unchanged value of σ_{yc}, which, in accordance with Eq.(2), may be caused only by a decrease in cleavage stress.

The influence of preliminary cyclic plastic deformation on

K_{fc}^{I} and K_{fc}^{k} is similar.

A further increase in K_{1c} of 15Kh2MFA(I) steel (Fig.1) with an increase in the preliminary number of cycles depends upon the features of formation of the microstructure of the material.

The development of surface microcracks in specimens of 15Kh2MFA(I) and 15Kh2MFA(II) steels during fatigue tests were investigated. In 15Kh2MFA(I) steel microcracks, the size and density of which increase with a further increase in the number of cycles, are formed even in the early stages of cyclic loading with an amplitude of elastoplastic deformation of $\varepsilon_a = 0.3\text{-}0.7\%$.

If the size of the plastic zone at the crack tip r_y is less than the average distance between microcracks $\bar{r}$ then preliminary cyclic plastic deformation leads to a reduction in K_{1c}, K_{fc}^{I}, and K_{fc}^{k} but with $r_y > \bar{r}$ an increase in the number of cycles the value of $K_{1c}(K_c)$ of 15Kh2MFA(1) at 123 K increases. Since in all cases the transitoin to brittle fracture in cyclic loading (K_{fc}^{I}, K_{fc}^{k}) occurs with $r_y < \bar{r}$, there is not an increase in K_{fc}^{I} and K_{fc}^{k} with an increase in the number of cycles.

On the basis of an analysis of the experimental data we obtained an approach that has been proposed to predicting the influence of preliminary cyclic plastic deformation on brittle fracture resistance. Let us consider the schematic relationship of the static fracture toughness of 15Kh2MFA(I) steel at 123°K and of 15Kh2MFA(II) at 293°K to the accumulated energy of inelastic deformation.

For 15Kh2MFA(II) steel the fracture toughness K_{1c} taking into consideration preliminary cyclic plastic deformation (Fig.2) is determined as follows:

$$K_{1c}^{pr} = K_{1c} + \Delta K_{1c}(\sigma_y) - K_{1c}(W), \qquad (3)$$

where K_{1c} is the fracture toughness of the original material; $\Delta K_{1c}(\Delta\sigma_y)$ is the change in fracture toughness as the result of the Bauschinger effect (area I in Fig.2) and $K_{1c}(W)$ is the change in fracture toughness caused by the energy of inelastic deformation dissipated in the material in cyclic loading (area II).

With the use Eq. (2) and (3) we obtain

$$K_{1c}^{pr} = K_{1c} + (\sigma_c / 7.431)^3 (\sigma^{-2}_{yc} - \sigma^{-2}_{y}) - k_W W, \qquad (4)$$

where σ_{yc} is determined from the result of investigation

of the rules of inelastic cyclic deformation in the area of stabilization at a given amplitude of elastoplastic deformation; the parameter k_W characterizes the intensivity of embrittlement of the material in cyclic loading and has the dimension MPa$\sqrt{m}$/(MJ/m^3).

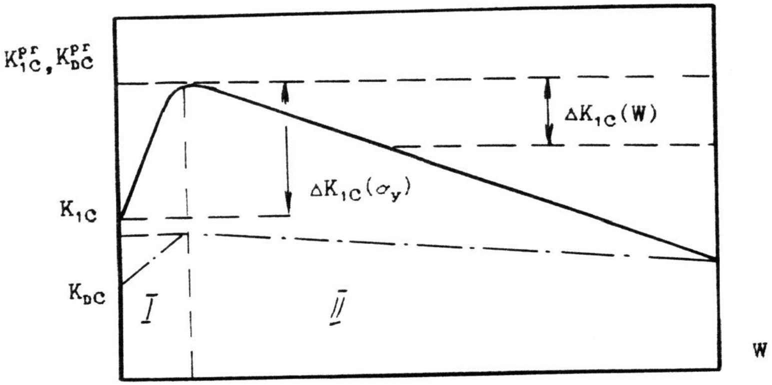

Fig.2. Schematic relationships of the static fracture toughness of 15Kh2MFA(II) steel to the accumulated energy of inelastic deformation.

As follows from Fig.1, the calculated and experimental relationships agree satisfactorily. The greatest error (32.9%) corresponds to a relative number of cycles of $\bar{N} = 0.85$ with $\varepsilon_a = 0.7\%$.

In analogy with Eq.(4) the dynamic fracture toughness of 15Kh2MFA(II) taking into consideration preliminary cyclic plastic deformation (Fig.2) is

$$K_{DC}^{pr} = K_{DC} + (\sigma_c / 7.431)^3 (\sigma_{dp}^{-2} - \sigma_d^{-2}) - k_{Wd} W, \qquad (5)$$

where σ_d and σ_{dp} are the dynamic yield strengths of the original material and the material subjected to preliminary cyclic plastic deformation, respectively, and K_{DC} is the dynamic fracture toughness of the original material. The coefficient k_{Wd} is determined similarly to k_W.

Therefore preliminary elastoplastic deformation in the stage before crack origin has a significant influence on the characteristics of brittle fracture resistance under static, cyclic and dynamic loads, which must be taken into consideration in calculations of the life of critical structures based on the criteria of brittle strength.

CONCLUSIONS

It has been established that depending upon the degree of embrittlement of the material and also upon the preliminary cyclic plastic deformation and test temperatures preliminary cyclic plastic deformation differently influences the brittle fracture resistance of 15Kh2MFA steel.

While in the initial stages the change in K_{1c} is caused by the change in yield strength as the result of the Bauschinger effect, with a larger number of cycles the total energy of inelastic deformation and the structural changes in the material related to it are the determining factors.

A method is proposed for predicting the influence of preliminary cyclic plastic deformation on the brittle fracture resistance of cyclically softening steels.

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