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LIFETIME EVALUATION FOR REACTOR STEELS UNDER LOW-CYCLE LOADING AT COMPLEX STRESS STATE

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ABSTRACT

The results of an experimental investigation into cyclic creep and low-cycle fatigue of heat-resistant steels in the initial state and after the thermal treatment simulating the metal embrittled by irradiation and of chromium-nickel stainless steel under repeating loading of various types are presented. The influence of the stress state type and the temperature upon their life is studied. Basing on the analysis of plasto-elastic properties of the materials studied making use of the viscoelastoplastic model of straining developed previously, a calculation and experimental method for life evaluation of structural steels under cyclic loading at the complex stress state is developed.

INTRODUCTION

The progress of investigations directed toward the comprehensive study of mechanical properties of structural materials under conditions of cyclic loading at the complex stress state and high temperatures is due to the continuous rise of the power equipment performance ratings while maintaining the requirements for guaranteed reliability of its service. Therefore, the investigation into the processes of cyclic creep and low-cycle fatigue of reactor steels aimed at development and justification of the validity of evaluation methods for their serviceability in products during the estimated service time taking into account the specific conditions of thermal and mechanical loading and metal structure is of great scientific and practical use.

PROCEDURE, RESULTS AND THEIR DISCUSSION

On testing under cyclic loading conditions making use of thin-walled tubular specimens ($D/\delta = 50$, where D is the inner diameter of the specimen, is the specimen wall thickness), the trapezoidal cycle loading was realized by a pulsating axial force and an internal pressure of various combinations with the rate of 2 cycles/min and the holding under the maximum loading during 6s. Tests were performed with the following ratios of the principal stresses: $K = \sigma_z/\sigma_\theta = \infty$, 2.1 and 0.5 where σ_z is the axial stress, σ_θ is the tangential stress. Experiments were carried out at temperatures of 20, 270 and 350^{o}C (steels 15Kh2MFA and 15Kh2NMFA in the initial state and after heat treatment) and also at 20, 285 and 320^{o}C (steels 106N2MFA and 08Kh18N10T-VD). The maximum stresses of the cycle (by the intensity of stresses) were given by the such ones as to ensure the specimen fracture for life times not exceeding $2 \cdot 10^4$ cycles which is in agreement with $\sigma_{i\,max} \geq 0.8\sigma_{ib}$, where σ_{ib} is the intensity of stresses at the given type of the stress state that corresponds to the specimen fracture under conditions of single-load application. For the steels studied the existence of a generalized stress-strain diagram invariant to the type of the stress state at all the above mentioned levels of temperatures was proved experimentally. This allowed to make use of the stress intensities, σ_i, and the strain intensities, ε_i, accordingly, as the strength and strain characteristics under cyclic loading.

To evaluate the viscoelastic properties of the steels studied, the earlier developed method of step loading was used whereby the balanced (quasi-static) stress-strain diagrams were received [4].

The experiments were carried out on a test bench SNT-8U described in details in [1] which allowed to test tubular specimens under the static step and cyclic loading at the plane stress state in a wide range of temperatures.

Estimating the influence of the stress state type on the plastic strain intensity at fracture of the steels studied we note that under conditions of a single load application the minimum irreversible strain is observed in nonuniform biaxial tension with the principal stress ratios ($K = 2$ and 0.5), the results which agrees with the known experimental data for a wide range of structural materials [2].

The analysis of viscoplastic properties of steels by the step-straining method [8] has shown that the relationships between viscous and plastic components of the strain rate depends upon the value of irreversible strain and the rate of straining. It was experimentally found that the condition of the strain localization depends significantly on the stress state type. Under the applied single loading it corresponds to the maximum on the stress-strain diagram. Many materials, including the materials studied, have a sufficiently long portion corresponding to the maximum stresses. This points to the fact that the equilibrium state between strain hardening processes of the material and the reduced bearing capacity of the specimen under test due to the change of its geometry dimensions and the form under straining can be retained in a sufficiently wide range of strains.

As indicated in [4], the similar states may be realized under conditions of the cyclic creep as well, namely, at the portion of the steady-state creep where the processes of the material strain hardening and the reduced bearing capacity of the structural component under test during the cyclic loading are balanced mutually. Hence, it follows that the quasi-static fracture both under applied single loading and under the cyclic loading should occur as a result of the exhaustion of the material plasticity and in both cases it should occur at the same levels of plastic strain for the specified type of the strain state and the temperature. This assumption has received the experimental validation at various relationships of the principal stresses and temperatures for the steels studied [5].

The analysis of creep curves obtained under repeating loading testifies that the stress state type has an essential influence on their nature. In particularly, under repeated static loading in conditions of nonuniform biaxial loading the portions of the steady-state creep are shortened in comparison with the same portions of curves obtained under conditions of the uniaxial tension over the entire temperature range studied.

It is known that the metal life, its cyclic strength and the failure nature are determined by the intensity of cyclic creep processes [6]. Therefore, the cyclic creep curves obtained were used to define the intensities of steady-state creep rates depending on the level of the maximum cycle stress intensities in the uniaxial and biaxial tension and at different temperatures. The analysis of these data together with the cyclic creep curves allows to conclude that the stress state type has a great influence upon the ability of the steels studied to resist to cyclic creep. In particular, the superposition of the second tension component of stresses both at room and at elevated temperatures results in increased ability of the metal to resist to cyclic creep with a simultaneous reduction of a resistance to fatigue fracture in comparison with the such one under conditions of uniaxial tension at the same levels of maximum stresses of the cycle. We note that in case of biaxial tension the zone of transition from fatigue fracture to quasi-static fracture shifts to the region of high creep rates in comparison with the case of uniaxial tension.

A rise in test temperatures in the range covered results in increased cyclic creep resistance of the heat-resistant steels studied.

Estimating the stress state type influence on the nature of the low-cycle fatigue curve we note that in biaxial repeating tension the portion of no-fracture on these curves is substantially reduced in comparison with the existing portions of the low-cycle fatigue curves in uniaxial tension. The comparison of the low-cycle fatigue curves for uniaxial and nonuniform biaxial tensions allows to conclude that the superposition of the second tensioning component of stresses shifts the quasi-static-to-fatigue fracture transition zone toward the region of lower life times at the same (by intensity) maximum cycle stresses.

An elevation of test temperatures for heat-resistant steels also causes the similar shift of the transition zone from quasi-static fracture to fatigue one on low-cycle fatigue curves toward the region of the lower life times for all the realized ratios of the principal stresses. In this case, the above feature is traced the most clearly for steel 10GN2MFA. Simultaneously we note that an increase of the test temperature results in a change of the nature of steel low-cycle fatigue curves. In particular, at 270 and 285°C the regions of quasi-static fracture on the curves are absent and at higher temperatures (350 and 320°C) the portions of quasi-static fracture appear again but they are somewhat smaller than the similar ones at room temperature. At the same time, for steel 08Kh18N10-20 all three specific portions of the low-cycle fatigue curve are retained over the entire range of temperatures studied.

The above features of the stress state type influence upon the nature of the limit curves of cyclic creep and the curves of low-cycle fatigue are practically the same both at room and at elevated temperatures.

The characteristic feature of low-cycle fatigue under the repeating stress-controlled loading is the presence of two fracture regions sufficiently extended toward the longer lifetime – the quasi-static and the fatigue ones. For quasistatic fracture conditions the rate of accumulated irreversible strains is in direct relationship to the material life exhaustion. In case of fatigue fracture, the life is determined by a rate of the crack onset and development process which are also governed eventually by the cyclic creep rate being here an indirect characteristic of the life exhaustion intensity. It should be noted that the character of the calculated dependence in estimating the material life for two indicated types of fracture can be different as the different (in their nature) processes are the basis for this.

In case of quasi-static fracture as is shown in [4, 8] rather promising results may be obtained with the use of relationships of a deformation-kinetic character in which the correlated parameters are the intensity of deformation processes and the life.

Having regard to this fact, a deformation-kinetic criterion [8] was proposed and substatiated physically at the Institute for Problems of Strength of the Academy of Sciences of Ukraine and on its basis a calculation and experimental method for the steel life evaluation in case of quasi-static fracture under repeating low-cyclic loading at the complex strain state [4] was devised.

The calculated relationship takes the form:

$$N_b = \frac{C_i}{a(\sigma_{i\max} - \sigma_{itr})^{b+1}} \tag{1}$$

where N_b is the number of cycles before fracture; C_i is the parameter which in a general case is dependent on the material deformation properties and is independent on the stress level in a cycle for a specified ratio of principal stresses. The parameter is determined from the condition of plastic strain stability loss; a, b are the material constants at particular temperatures determined by characteristics of viscoplastic properties of materials [3, 4]; σ_{itr} is the stress intensity of the transition from a fatigue fracture to a quasi-static one which is calculated for the different ratios of principal stresses making use of the condition of plastic strain stability loss on the basis of the transition stress defined experimentally at uniaxial repeating tension. The detailed calculation and experimental method of the life evaluation is given in a publication [4].

Rather large scope of investigations conducted on heat-resistant steels and a metastable steel has validated the high reliability of eq.(1), as evidenced by the results in Fig.1. As is seen, for some of the steels studied a satisfied agreement between the estimated values of life and the experimental ones is observed with all the realized relationships of the principal stresses and temperatures of 20, 320 and 350°C when the fracture develops by a quasi-static mechanism.

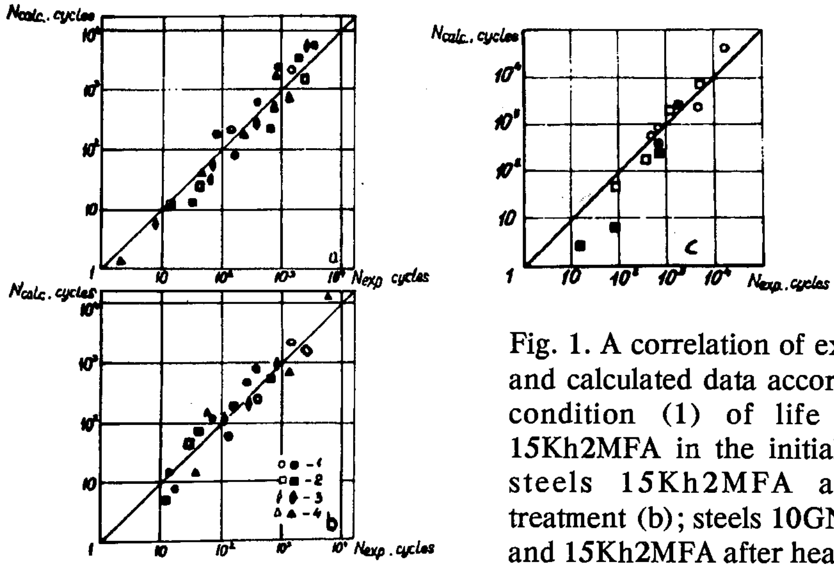

Fig. 1. A correlation of experimental and calculated data according to the condition (1) of life for steels 15Kh2MFA in the initial state (a); steels 15Kh2MFA after heat treatment (b); steels 10GN2MFA (c) and 15Kh2MFA after heat treatment.

CONCLUSIONS

1. It is found that the type of stress state has an important influence on the evolution nature of cyclic creep and low-cycle fatigue processes for structural steels over the studied range of temperatures. In particular the transition from uniaxial repeating tension to nonuniform biaxial one results in higher resistance of steels to cyclic creep with simultaneous decreased resistance to fatigue failure both at room and elevated temperatures.

2. The calculation and experimental method of life evaluation under repeating low-cycle loading at the complex stress state basis starting from the limited volume of relatively simple base testing is proposed and substantiated experimentally.

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