LIFE ASSESSMENT FOR HEAT-RESISTANT STEELS UNDER REPEATING STRESS-CONTROLLED LOADING AT THE COMPLEX STRESS-STATE CONDITIONS

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ABSTRACT

Basing on the earlier data analysis given for the viscoplastic material behaviour studies the method is suggested for the structural steels life assessment under conditions of cyclic loading at the complex stress-state making use of the plastic deformation stability loss requirement to assess the ultimate state.

INTRODUCTION

Under low-cyclic loading the structural component design normally involves either the component life prediction under the given loading conditions or its ultimate state assessment for the designed lifetime. For the both situations the initial parameters are taken to be the regime of the applied temperature and mechanical effects as well as the characteristics of the material mechanical behaviour.

It is known /1-3/ that under the stress-controlled loading conditions there exists the irreversible plastic deformation accumulation or cyclic creep. As is shown /1-4/ these conditions are fairly well described by the dependences with the lifetime being correlated by the deformation intensity parameter. These dependences are presented by a relation suggested by V.A.Strizhalo /1/ where, basing on the hypothesis of the similarity of the cyclic creep curves given in"the reduced strain ($\varepsilon/\varepsilon_f$) and the reduced number of cycles (N/N_b)" relative coordinates the stable creep rate ($\dot{\varepsilon}_{min}$), the number of cycles to fracture (N_b) versus the accumulated plastic strain ε_f relationship is written as

$$N_b \cdot \dot{\varepsilon}_{min} = \xi \cdot \varepsilon_f \qquad (1)$$

where ξ is the coefficient of similitude standing for the stable creep reduced rate (the slope of the cyclic creep curve in the relative coordinates).

Basing on the experimentally established requirement for the existence of the generalized stress-straining diagram for the materials studied it is in /5/ where the relation is suggested for the life assessment under complex stress-state conditions which structurally is similar to Strizhalo's equation

$$N_b \cdot \dot{\varepsilon}_{i\,min} = \xi_i \, \varepsilon_{ib} \qquad (2)$$

where $\dot{\varepsilon}_{i\,min}$ is the creep rate minimum intensity; ε_{ib} is the intensity of the plastic strains accumulated to fracture which is taken to be equal to that of plastic strains corresponding to single-loading fracture; ξ_i is the coefficient having the same physical meaning for the given type of the stress-state as in Eq.1. Nevertheless, having obtained a fair agreement beetween the calculated data through Eq.2 and the experimental evidences /4,6,7/, the possibilities for the wide usage of this criterion are limitted by the necessity of conducting a great deal of basic studies.

THE TECHNIQUE, RESULTS AND THEIR DISCUSSION

Basing on the elasto-viscoplastic model /8/ developed at the Institute for Problems of Strength of the Ukrainian SSR Academy of Sciences as well as experiments conducted for studying the structural steels viscoplastic behaviour /9/, it is possible to find the ways for simplifying and reducing the number of basic experiments required for getting the sufficient initial basic data.

Write Eq. 2 as

$$N_b \dot{\varepsilon}_{i\,min} = C_i \qquad (3)$$

where $C_i = \xi_i \varepsilon_{ib}$ is the parameter which in a general case is dependent on the material stress-strain behaviour and is not dependent on the stress level in a cycle for the given ratio of the principal stresses. Equation 2 yields that C_i can be considered as the creep strain accumulated in service at the creep rate equal to $\dot{\varepsilon}_{i\,min}$

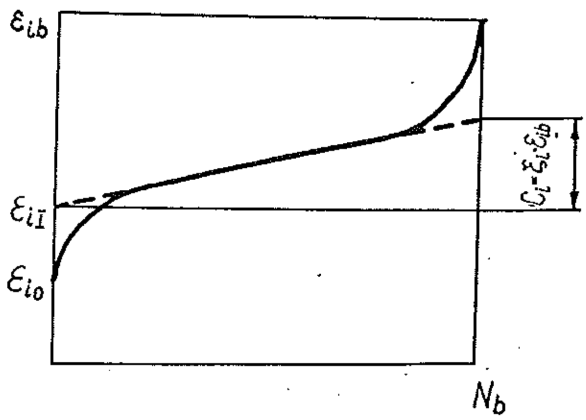

Fig. 1. Typical diagram for the creep resultant in the component quasi-static fracture at load.

If under cyclic loading the material fracture occurs through the quasistatic mechanism then similarly to the stress-strain kinetics for the case of single loading it could be assumed firstly that in course of service there will exist the improvement of material resistance due to its strain hardening and secondly the reduction of the studied component carrying capacity due to the geometry and dimensions variation, e.g. necking the cross section of a tubular specimen subjected to cyclic tension. At the first creep stage the reduction in specimen carrying capacity due to its actual cross-section is balanced by the material strain hardening. Hence the creep processes occur with the diminishing rate. The second creep stage ($\dot{\varepsilon} = \dot{\varepsilon}_{min}$) corresponds to the balanced state with its possible duration varying and being dependent on the material capacity of hardening, specific features of the specimen design and the material stress state. Gradually the creep process gets activated and proceeds with the accelerating rate (the third stage).

Thus the second stage (the balanced stage) is adequate to the plastic deformation stability loss requirement which for the biaxial tension ($K = \sigma_z/\sigma_\theta = 0 \dots \infty$) may be given as:

- in the region $K = 0 \dots 1$

$$\left(1 + \frac{2K-1}{2\sqrt{K^2-K+1}}\,\varepsilon_i\right)\frac{\sigma_b^{un}}{1+\varepsilon_b^{un}} = \sigma_{eq}(\varepsilon_i)$$

or

$$\left(1 + \frac{2K-1}{2\sqrt{K^2-K+1}}\,\varepsilon_i\right)\left(1 + \frac{2-K}{2\sqrt{K^2-K+1}}\,\varepsilon_i\right)\frac{\frac{2}{\sqrt{3}}\,\sigma_{ib}^{b}}{\left(1+\frac{\sqrt{3}}{2}\,\varepsilon_{ib}^{b}\right)^2} = \sigma_{eq}(\varepsilon_i) \quad (4)$$

- in the region $K = 1 \dots \infty$

$$\left(1 + \frac{2K-1}{2\sqrt{K^2-K+1}}\,\varepsilon_i\right)\frac{\sigma_b^{un}}{1+\varepsilon_b^{un}} = \sigma_{eq}(\varepsilon_i)$$

where σ_b^{un} , σ_{ib}^{b} and ε_b^{un} , ε_{ib}^{b} are the limiting stresses and the respective uniform plastic strains for uniaxial and biaxial loading.

The geometrical representation for the solution of Eq. 4 is the diagram given in Fig. 2. It involves the generalized curve $\sigma_{eq}(\varepsilon_i)$ as well as those describing the fracture of the structural component in its deformation.

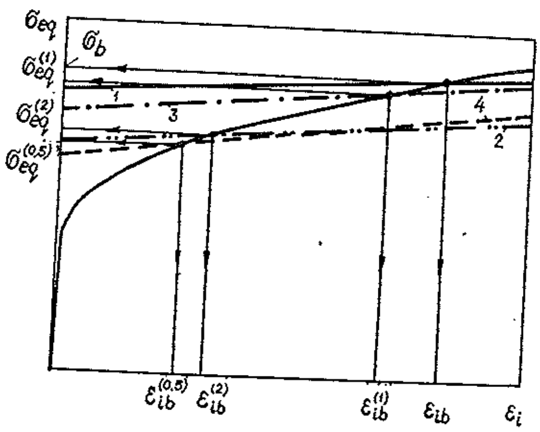

Fig. 2. Graphic representation of equation (4) for various principal stress ratios:
1 - $K = \sigma_z/\sigma_\theta = \infty$; 2 - $K = 2$; 3 - $K = 1$; 4 - $K = 0.5$.

Using this diagram, as is shown from the figure, stresses and strains as well as the pertinent losses in the carrying capacity of the component could be readily determined with the principal stresses ratio ranging over $K = 0 \dots \infty$. Furthermore the special test data showed that for the given principal stresses ratio the cotangent of the angle between the fracture curves and the generalized one $\sigma_{eq}(\varepsilon_i)$ is in correlation with the parameter C_i for the same stress ratio. The validity of this experimentally observed evidence is proved by the coincidence of this angle cotangent values and those of the parameter C_i for the ultimate transitions. In the case $C_i = 0$ (material exercises brittle fracture) the curves intercept practically at a right angle and on the other hand, at $C_i = \infty$

(material exercises plastic deformation without a deformation limit) the fracture curves intercept with the curve $\sigma_{eq}(\varepsilon_i)$ at a very small angle.

Accordingly due to the proportionality of the above angles and the parameter C_i values for a certain given (arbitrary) stress state and in uniaxial tension which are considered to be the base test condition we obtain

$$C_i = C_{un} \frac{ctg\,\alpha_i}{ctg\,\alpha_{un}} \qquad (5)$$

where C_{un} is obtained using the cyclic creep curve under uniaxial repeating tension conditions (see relation 3) and the cotangents for the angles α_i and α_{un} are calculated through one of the relations resultant from (4):

- in the region with $K = 0 \ldots 1$

$$ctg\,\alpha_i = \left(\frac{d\sigma_{eq}(\varepsilon_i)}{d\varepsilon_i} - \frac{\sqrt{3}\,\sigma_{ib}^{b}}{1+\frac{\sqrt{3}}{2}\varepsilon_{ib}^{b}}\right)^{-1} \qquad (6)$$

- in the region with $K = 1 \ldots \infty$

$$ctg\,\alpha_i = \left(\frac{d\sigma_{eq}(\varepsilon_i)}{d\varepsilon_i} - \frac{2K-1}{2K}\,\frac{\sigma_b^{un}}{1+\varepsilon_b^{un}}\right)^{-1}$$

Criterion 3 along with C_i involves the parameter $\dot{\varepsilon}_{i\,min}$ standing for the minimum creep rate which is determined through the following assumptions.

The material creep is considered to be resultant from the local elastic stress relaxation in a crystal lattice which arises in the process of active deformation. The material relaxation behaviour is fairly well described by "the balanced states diagram" which in its physical meaning is adequate to the stress-strain diagram with the strain rate tending to zero /8,10/.

The authors developed a comparatively simple technique for constructing this diagram in step cyclic loading testing /9/. The results of the tests conducted proved the above curve to be invariant with respect to the stress state.

The stress-strain curve for the ultimate strain rate will be located above the balanced one whereas the stress σ corresponding to any given strain ε could be presented as a sum of the balanced stresses $\sigma_{bal}(\varepsilon_i)$ and some excessive stresses $\sigma^*(\varepsilon)$ (un-balanced) which constitute the creep, rate at the stress $\sigma(\varepsilon)$, i.e. at the initial strain ε.

Provided k_i is a certain parameter standing for viscosity coefficient, $\dot{\varepsilon}_{i\,cr}$ is the creep rate intensity for the unbalanced stress σ_i^* ; then using a nonlinear Newton model we obtain

$$\dot{\varepsilon}_{i\,cr} = k_i(\sigma_i^*)\,\sigma_i^* \qquad (7)$$

Using the available experimental data /8/ we assume

$$k_i(\sigma_i^*) = a(\sigma_i^*)^b \qquad (8)$$

where a , b are the material constants for the specific temperature conditions determined by the two basic test data under uniaxial repeating tensiton.

In fact, (7) with the account taken of (8) could be given as

$$\dot{\varepsilon}_{i\,cr} = a(\sigma_i^*)^{b+1} \qquad (9)$$

or in the logarithmic coordinates

$$\ln \dot{\varepsilon}_{i\,cr} = \ln a + (b+1)\ln \sigma_i^*$$

With respect to the two tests conducted at stresses $\sigma' = \sigma^{*\prime} + \sigma'_{bal}$ and $\sigma'' = \sigma^{*\prime\prime} + \sigma''_{bal}$ under conditions of the uniaxial tension we obtain

$$\begin{aligned} \ln \dot{\varepsilon}'_{un\,cr} &= \ln a + (b+1)\ln(\sigma^{*\prime} + \sigma'_{bal}) \\ \ln \dot{\varepsilon}''_{un\,cr} &= \ln a + (b+1)\ln(\sigma^{*\prime\prime} + \sigma''_{bal}) \end{aligned} \qquad (10)$$

where $\dot{\varepsilon}'_{un\,cr}$ and $\dot{\varepsilon}''_{un\,cr}$ are the creep rates in uniaxial tension.

Solving these equations we obtain the values of the constants a and b having determined σ'_{bal} and σ''_{bal} using the respective values of the initial strains from the balanced diagram.

The range for using the criteria of types (1), (2) and (3) is limited by the quasistatic-to-fatigue transition stress $\sigma_{i\,tr}$ fracture mechanism where the transition stress levels appeared to be dependent on the stress state whereas could be determined for any value of $K = \sigma_z/\sigma_\theta$ using the deformation stability loss requirements (see Eqs. 4) where the equation of the generalized curve $\sigma_{eq}(\varepsilon_i)$ is replaced by that of the quasistatic curve $\sigma_{i\,bal}(\varepsilon_i)$.

Constructing the graphs in a similar way which is given above it is possible to calculated the values of the transition stress $\sigma_{i\,tr}$ for any ratio of principal stresses over the range $K = 0 \dots \infty$. Here the data required for calculation are obtained using the experimental low-cycle fatigue curves with respect to the transition stresses for two the most readily attained types of the stress state under cyclic loading (e.q. uniaxial repeating tension and repeating internal pressure).

From the point of view of the plastic deformation stability loss requirement $\sigma_{i\,tr}$ could be considered to be the maximum stress when the balanced stress state and the fatigue fracture could be attained. Therefore the lowest unbalanced stress governing the lowest cycle creep rate $\dot{\varepsilon}_{i\,min}$ in quasistatic fracture will be given as

$$\sigma_i^* = \sigma_{i\,max} - \sigma_{i\,tr}$$

using (9) we obtain

$$\dot{\varepsilon}_{i\,min} = a\left(\sigma_{i\,max} - \sigma_{i\,tr}\right)^{b+1}$$

or basing on (3)

$$N_b = \frac{C_i}{a\left(\sigma_{i\,max} - \sigma_{i\,tr}\right)^{b+1}} \qquad (11)$$

The extensive test data for the reactor steels proved a high efficiency of criterion II having conducted a comparatively small number of basic tests showed in Figure 3. As is seen a fair agreement is observed for the life calculation and experimental data for all principal stress ratios in testing the 15X2HMФA steel at the initial service stage and the 15X2MФA steel at the late service stage using the technique /11/ for thin-walled tubular specimens under stress-controlled proportional repeating loading.

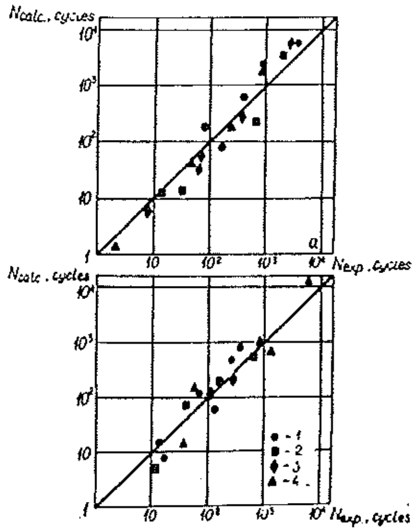

Fig. 3. The comparison of the experimental and calculated life for the 15X2MFA steel (a) in the late service stages and 15X2HMFA steel (b) in the initial stage at temperature 293° under complex stress state conditions: 1 - $K = \sigma_z/\sigma_\theta = \infty$; 2 - $K = 2$; 3 - $K = 1$; 4 - $K = 0.5$ using relation (11).

CONCLUSION

1. Basing on the experimental data obtained by the authors for the reactor pressure-vessel steels the technique is developed for the assessment stresses and strains corresponding to the structural component carrying capacity loss under biaxial cyclic loading conditions.
2. Using the elasto-visco-plastic model suggested along with the extensive experimental data on visco-plastic material behaviour, the calculation and experimental method is proposed for structural steels life estimates under complex stress-state conditions in cyclic loading which allows the labour consuming experiments to be simplified as well as the number of basic tests necessary for getting the sufficient initial data to be reduced.
3. The experiments performed allow the balance equation to be suggested which makes it possible to obtain the structural steels life estimates with the account taken for the type of the stress state in quasistatic fracture under repeating loading conditions.

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