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Low-cycle Fatigue of Anisotropic Steel under Nonproport ional Loading.

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Abstract: In the present paper low-cycle fatigue of anisotropic steels type 16Cr-9Ni-2Mo and 2Cr - Ni-Mo-V are considered under some plane proportional and nonproportional trajectories of loading. Is shown, that at certain orientation stress and strain concerning axes of anisotropy the fracture (crack initiation) occurs owing to stratification of material and takes place essentsial decrease of durability. Are offered and experimentally justified criteria of low-cycle fracture energy and strain type, enabling to determine value of accumulated damage and durability at given kinds of loading.

Introduction

A number of effects,wich cannot be obtained at proportional cyclic loading of materials appeares under complex trajectories with the turn of axes stress and strains tensors.It is additional cyclic hardening of materials, decrease of cyclic durability in comparison with case of proportional loading,dependence it from sequence of acting of shear and axial components of strain.

Alongside with marked, for anisotropic materials essential is the orientation axes of stress and strain tensor about of axes anisotropy, which can change along a trajectory nonproportional loading. In this case the choice more dangerous, from the point of view of influence on damage of material, component of stress and strain is ambiguous, so as realization of various mechanisms of destruction is possible.In this connection evalution low-cycle fatigue criteria for anisotropic materials under nonproportional loading is actual scientific problem wich is of interest for designer and engineers.

Materials and specimens

This paper deals with two anisotropic materials with contrast cyclic properties -cyclic hardening steel type16Cr-9Ni-2Mo and cyclic softening steel type 2Cr-Ni-Mo-V. Steel 16Cr-9Ni-2Mo was delivered in a form of rolled plate by thickness of 60 mm, steel 2Cr-Ni-Mo-V in a form of templet , cut out from forged shell by thickness of 160 mm. This materials are orthotropic, so it have three mutually perpendicular planes of symmetry of mechanical properties, and besides, as have shown results of tests have circular symmetry to the axis Z,which for steel 16Cr-9Ni-2Mo is perpendicular to the plane of rolling XY (axis X, Y - axis anisotropy), and the axis X corresponds to a direction of rolling.

For steel 2Cr-Ni-Mo-V the axis Z corresponds to a radial direction of shell, axes X and Y can be accepted as meredional and tangential directions.Anisotropy of this materials can be characterized only by one parameter - an angle between axis Z and direction of cutting of specimen. Designation of axes are shown on fig. 1, where axes X_1, Y_1, Z_1 -axes symmetry of specimen.

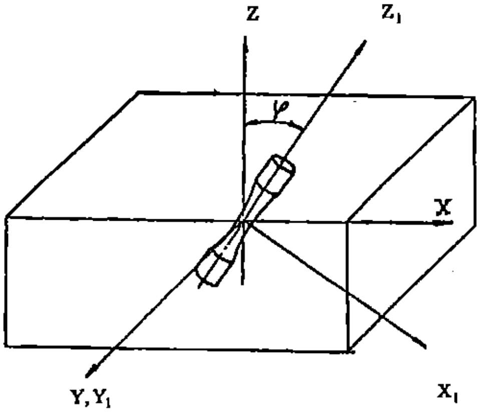

Fig. 1 Scheme of cutting of specimen.

The mechanical properties of investigated materials for various directions of cutting of specimen are shown in tab.1.

Table 1. Mechanical properties of materials

material	direction	yield stress, MPa	tensile strength, MPa	reduction in area, %
16Gr-9Ni-2Mo	X	280	600	55
	Y	240	575	56
	Z	270	580	26
2Gr-Ni-Mo-V	X	600	711	70
	Y	600	700	75
	Z	590	706	75

As follows from indicated data for steel 16Cr-9Ni-2Mo under tension in a direction of axis Z essential decrease (up to 2 times) reduction in area at fracture take place, other characteristics weak depend from direction of cutting. The static characteristics 2Cr-Ni-Mo-V steel were independed practically from a direction of cutting of specimen.

The cyclic tests of materials were conducted under tension - compression, torsion, as well as at combined loading by torque and axial force under strain-controlled conditions on various trajectories proportional and nonproportional loading.A specimen wos a tube with 30mm parallel gauge length,14mm external diametr and 10mm internal diametr.

Uniaxial loading

For steel 16Cr-9Ni-2Mo under cyclic tension-compression , as follows from fig. 2, data of tests X - specimens and specimens,cutting under a angle 45^0 to the axis Z ,fall practically on the same low-cycle fatigue curve . For Z - specimens essential decrease of cyclic durability ,approximately in 4 times is obtained. Similar reduction durability of Z - specimens is obtained and for steel 2Cr-Ni-Mo-V, fig. 3. Received data for steel 16Cr-9Ni-

2Mo corresponds with character of change of reduction in area at a static tension. For steel 2Cr-Ni-Mo-V the cyclic tests data of Z-specimens can not be predicted on the static characteristics.

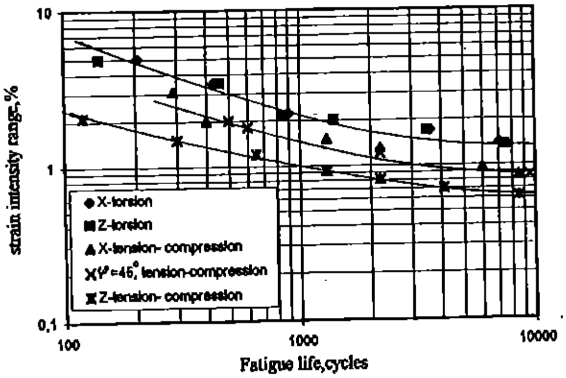

Fig.2 Low-cycle fatigue curve 16Cr-9Ni-2Mo steel

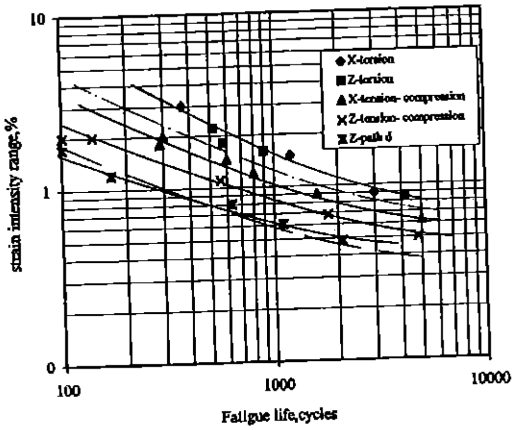

Fig.3 Low-cycle fatigue curve 2Cr-Ni-Mo-V steel

With purpose of more detailed study influence anisotropy on fatigue life cyclic tests of specimens,cutting under various angles $\varphi = 0 - 90^{\circ}$ to the axis Z through 15° were conducted. The results of this tests ($\Delta\varepsilon = \text{const}$) are shown on fig. 4,5. For both materials at $\varphi \leq 45^{\circ}$ takes place monotonic increasing of durability with increasing angle φ .

At φ > 45° experimental points have appeared are close to appropriate significances, received at tests of longitudinal specimens.

For the quantitative description of considered experimental data under tension - compression different approaches were evaluated. In the first case it was assumed, that the fracture is defined by normal strains, and at reasonably high significances of strains, normal to plane of rolling, occurs stratification of a material.

By use of Menson-Coffin equation, the condition of fracture with account stratification can be described by a ratio:

$$\Delta\varepsilon_j = C_{pj}N^{m_{pj}} + C_{ej}N^{m_{ej}} \tag{1}$$

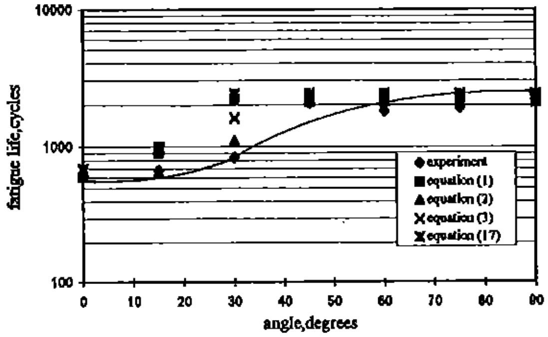

Fig.4 Change in fatigue life with varied angleφ (16Cr-9Ni-2Mo)

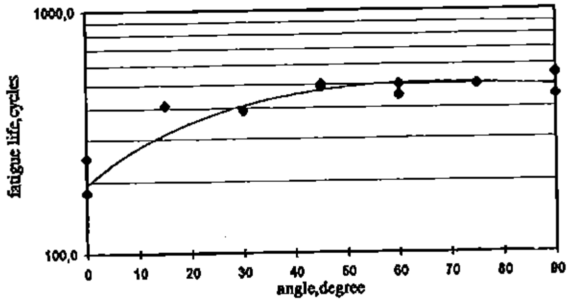

Fig.5 Change in fatigue life with varied angleφ (2Cr-Ni-Mo-V)

The first and the second members of right part (1) represent according dependences for a plastic and elastic component of strain. N - fatigue life (a number cycles before failure); C_{pj}, C_{ej} and m_{pj}, m_{ej} - accordingly coefficients and powers for plastic and elastic component of strain. The index j at parameters equation (1) specifies direction of normal strain. The most dangerous direction, which can be a line of action maximum strain (axis of symmetry of specimen) or axis Z (if takes place stratification) is defined from a condition of reception of minimum number of cycles on (1).

In the second approach it was accepted, that the process stratification is influenced by not only normal, but also shear strain, acting on planes, parallel to plane of rolling. In this case the equivalent strain wos used as parameter of fracture in form:

$$\Delta\varepsilon^{\otimes} = \left(p\Delta\varepsilon_Z^m + q\Delta\gamma_{XZ}^m\right)^{1/m} \qquad (2)$$

Where p , q and m - the constants of a material (for steel 16Cr-9Ni-2Mo p= 1,4; q = 0,6; m = 2). It was accepted, that at $\Delta\varepsilon^{\otimes} \le \Delta\varepsilon_1$ the fracture occurs without stratification. The ratio (2) also can be incorporated with a Menson-Coffin equation.

Alongside with strain, energy approach was used, accordingly which it was assumed, that the number of cycles before fracture is connected with plastic strains energy for a cycle by dependence:

$$N = F(W_p),$$

where F - some monotonic decreasing function of W_p.

For anisotropic material value W_p is possible to determine as

$$W_P = \int_\Omega \sigma_X d\varepsilon_X^p + \int_\Omega \tau_{XZ} d\gamma_{XZ}^p + k\int_\Omega \sigma_Z d\varepsilon_Z^p \qquad (3)$$

where the value of a weight factor *k* is defined by reduction of W_p - N curve for Z - specimens to appropriate curve, received under loading of specimens, cutting in a longitudinal direction, fig. 6.

The components of strain and stress, included in (1) - (3) were calculated on known dependences with the account of orientation axes of anisotropy concerning axes of symmetry of specimen.

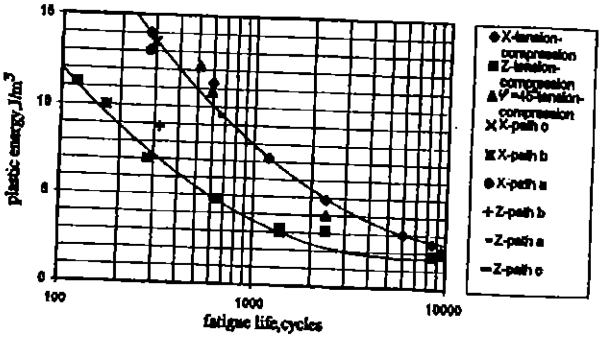

Fig.6 Relationship between plastic energy a number cycles of loading.

Above described approaches were used for evaluation a numbers of cycle before fracture (crack initiation) of 16Cr-9Ni-2Mo steel specimens,cutting under various angles to the axis Z. The received results, as well as data of experiment are shown on fig.4.

In according with criterion (1) stratification of a material occurs under condition of $\varphi_{cr} = 26°$ (φ_{cr} - critical angle). On criterion (2) $\varphi_{cr} = 35°$.At $\varphi > \varphi_{cr}$ the account on specified criteria gives identical significances of durability ($\Delta\varepsilon = \text{const}$) irrespective of value φ .As follows from fig.4 criterion (2), taking into account influence on stratification a shear components of strain gives more good results, than equation (1). Received on the basis of criterion (3) results are enough close to a data, given by ratio (2). As follows from fig. 4 by use considered equations a divergence of theoretical and experimental significances of durability not exceed 2 times, that is quite acceptable.

Combined loading

For research low-cycle fatigue under multiaxial stress and strain condition the tests of specimens of steels type 16Cr-9Ni-2Mo and 2Cr-2Ni-Mo-V were conducted under combined loading by torque and axial force on different proportional and nonproportional paths. Process of loading was executed with given significances axial and shear strains on a symmetric cycle, the trajectories were set in a kind of a beam, break line, circle, extended ellipse, fig.7,a-e. The trajectories b and c permit to reveal influence to durability of a sequence acting shear and axial strains, which determines a sign of a normal stress, acting in part of cycle with shear strain. Loading on a circular trajectory d gives a minimum durability and maximum cyclic hardening. For convenience of the analysis and comparison a results of experiment the value of axial and shear strain in extreme points of a cycle was equal for all trajectories.The tests were conducted on the specimens,cutting in X and Z directions.

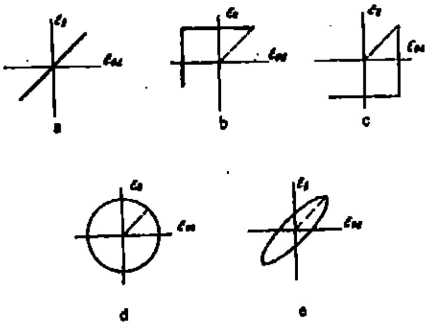

Fig.7 Paths of loading

Analysis results of tests on cyclic torsion has shown, that at a given kind of loading a number of cycles before fracture for both materials did not depend from a direction of cutting of specimens. The given tests X and Z - specimens fall on the same fatigue curve , fig.2, 3 and at identical value of strain intensity a number of cycles before fracture under torsion has appeared higher, than at tension-compression. The coincidence of durability X and Z -specimens under torsion is explained by identical orientation of axes anisitropy X and Z - specimens relateve applied stress and strains.

The tests under combined loading steel 16Cr-9Ni-2Mo have shown , that for a circular trajectory d and trajectory b, the durability X and Z - specimens has appeared below, than for a beam trajectory, in 2- 5 times. For trajectory c is obtained increasing value of durability in comparison with trajectories b and d.Data of tests on a trajectory e in a kind extended ellipse have appeared close to results, received for beam loading. We shall note also, that at combined loading distinction in value of durability X and Z - specimens, tested at identical range of strains has appeared below, than in case of tension - compression.

The tests of 2Cr-Ni-Mo-V steel specimens were conducted on a circular strain trajectory , giving by maximum damaging effect. The low-cycle fatigue curve (3) received for this regime is shown on fig. 3. As well as for steel 16Cr-9Ni-2Mo wos obtained reduction of cyclic durability, which in comparison with tension- compression makes 3-4 times.

Decrease of durability under nonproportional paths of loading the authors of Ref.(1) connect with additional cyclic hardening and increase of the area of loops of a hysteresis. In the present research this effects were also obtained for trajectories b, c,d.Additional increase of stress for stell 16Cr-9Ni-2Mo at nonproportional loading, in comparison with case of uniaxial cyclic loading, made up to 25 % (at a identical level of strains range). For trajectory in a form of extended ellipse additional hardening is not marked, in view of a small deviation of a given kind of loading from beam path.

The observed increase of durability at loading on a trajectory c in comparison with trajectories b,d can be explained by influence of compressing stress and strain, acting on more, than in other cases, part of a cycle of loading. A consequence it was also loss of stability of specimen , tested on a trajectory c ($\Delta\varepsilon_Z$ =2,0 %; $\Delta\gamma_{XZ}$=1.72%), while for other paths, at same significances ranges of strains, given effect was not found.

We shall note, that at cyclic torsion a cracks were developed lengthways and across axis of specimens, in conditions of tension - compression and combined loading a cracks were oriented perpendicularly or with inclination to the axis of specimen.

By use of the energy approach decrease of cyclic durability at nonproportional loading can be connection with increase of the area of a hysteresis loops (2).

As is known, the complete energy of deformation W can be submitted in a kind of a sum plastic Wp and elastic We energy:

$$W = W_p + W_e \tag{4}$$

And for uniaxial loading

$$W_p = \int_{\Omega} \sigma d\varepsilon_p = C_o \sigma_o \Delta\varepsilon_p \tag{5}$$

$$W_e = {}^1\!/_2\, \sigma_o \Delta\varepsilon_e \tag{6}$$

where σ_o - maximum stress of a cycle; $\Delta\varepsilon_p$, $\Delta\varepsilon_e$ - ranges of plastic and elastic strains; C_o - parametr, depending from the form stress-strain curve (C_o = 0,5 - 1,0).

In agreement with a Menson-Coffin equation the ranges of the plastic and elastic strains connect with the number of cycles before fracture by following equotions:

$$\Delta\varepsilon_p = C_p N^{m_p} \tag{7}$$

$$\Delta\varepsilon_e = C_e N^{m_t} \tag{8}$$

Having substituted (7) and (8) in (5) and (6) it is possible to receive:

$$W_p = C_o C_p \sigma_o N^{m_p} \tag{9}$$

$$W_e = \frac{1}{2} C_e \sigma_o N^{m_e} \tag{10}$$

We shall note, that criteria (9) and (10) at tension - compression identically go in (7) and (8), and the numbers of cycles before fracture for given case of loading on criteria (9) and (10) coincide owing to one-valued connection between $\Delta\varepsilon_p$ and $\Delta\varepsilon_e$ at uniaxial loading.

It is possible to assume, that criteria (9) and (10) are correct and in the case of nonproportional loading. Thus, if accept, that the fracture occurs due to normal stress and strain (crack type I), value W_p and W_e follow interpret as a part of general energy , appropriate normal component of stress and strain:

$$W_p = C_1 \sigma_1 \Delta\varepsilon_{1p} \tag{11}$$

$$W_e = \frac{1}{2} \sigma_1 \Delta\varepsilon_{1e} \tag{12}$$

The constant C_1 in (11) similarly (5) is defined by stress-strain curve $\sigma_1 - \varepsilon_{1p}$ for nonproportional loading.

Having substituted (11) and (12) in (9) and (10) we shall receive:

$$\frac{C_1\sigma_1}{C_o\sigma_o}\Delta\varepsilon_{1p} = C_p N^{m_p} \qquad (13)$$

$$\frac{\sigma_1}{\sigma_o}\Delta\varepsilon_{1e} = C_e N^{m_e} \qquad (14)$$

We shall note, that at nonproportional loading the number of cycles before fracture, predict by criteria (13) and (14) can be vary by virtue of addition cyclic hardening, difference of the form stress-strain curve and relation of a elastic and plastic components of strain in comparison with uniaxial loading. For average valuation of durability (13) and (14) can be united to receive thus following criterion of fracture:

$$\frac{\sigma_1}{\sigma_o}\left(\frac{C_1}{C_o}\Delta\varepsilon_{1p} + \Delta\varepsilon_{1e}\right) = C_p N^{m_p} + C_e N^{m_e} \qquad (15)$$

The right part of criterion (15) corresponds to a Menson-Coffin equation for uniaxial loading. In a left-hand part the relation stress σ_1/σ_o is similar correction factor of Smith-Watson-Topper (1). The value of the relation C_1/C_o is determined by difference of the form stress-strain curve under tension - compression and nonproportional loading. If these distinction is negligible, Smith-Watson-Topper criterion follows from (15).

For the description conditions of fracture anisotropic materials under nonproportional loading on type I strain criteria in form (1) and (15) can be incorporated in a kind:

$$\frac{\sigma_j}{\sigma_{oj}}\left(\frac{C_j}{C_j}\Delta\varepsilon_{pj} + \Delta\varepsilon_{ej}\right) = C_{pj} N^{m_{pj}} + C_{ej} N^{m_{ej}} \qquad (16)$$

where σ_{oj} and σ_j - maximum normal stresss on plane with normal j, acting accordingly at proportional and nonproportional loading (at equal strain range). The other parameters are identical ones used in (1) and (15), but are calculated for plane with normal j. The most dangerous direction is direction, for which calculated number of cycles is minimum.

For the description of fractures at nonproportional loading due to normal stress and strain (cracks type I) was used also purely energy approach at which as parameter of destruction the work of normal stress on appropriate plastic strain is accepted:

$$W_p = \int_{\Omega} \sigma_j d\varepsilon_{pj} \tag{17}$$

Thus the number of cycles before fracture will be defined on curves W_p - N for X and Z - specimens. Choice of orientation of plane,characterized by normal j,on which integral in (17) is calculated, is determined from codition of minimum number of cycles on the dependence W_p - N.

Considered above dependence (16) and (17) were evaluated for estimation life of 16Gr-9Ni-2Mo steel specimens, tested on path a - e, fig. 7, as well as at torsion.

By use the criterion (16) in cases loading Z - specimens minimum numbers of cycles were received for plane normal to the axis of specimen. For X - specimens the minimum number of cycles is received for plane, normal to which makes with the axis of X - specimens the angle 25^{0} (that approximately corresponds direction $\Delta\varepsilon_{1\max}$).

In cases torsion X and Z -specimens the most dangerous is direction main strain. As follows from comparison calculated on (16) and experimental significances cyclic life, in all cases of loading except for a path c, the divergence does not exceed 2 times, fig.8.

For the coordination of results of account and experiment on a path c it is necessary to enter additional parametr, reflecting more intensive, in this case, effect compressing strain. As such parameter it is possible, for example, to accept valuc

$$P = \int_{\Omega} \varepsilon_n^{(c)} dL \Big/ \int_{\Omega} \varepsilon_n^{(t)} dL$$

where $\varepsilon_n^{(c)}, \varepsilon_n^{(t)}$ - accordingly normal compressing and tension strain ;

L - length of a strain path.

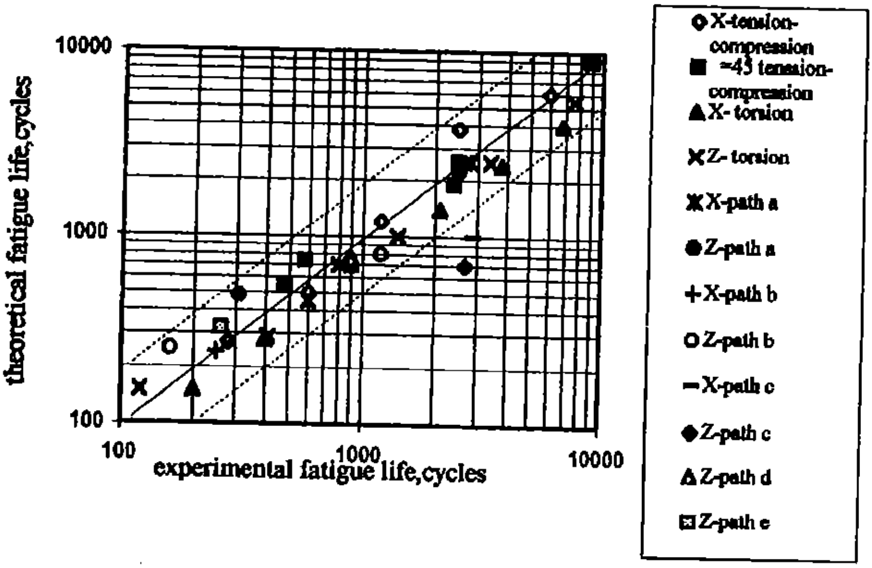

Fig.8 Correlation experimental and theoretical cyclic life

Using fig. 7 it is possible to receive, that for symmetric cycles (path a,d,e) $P = -1$, for a path c $P = -5$. As foolows from comparison of results, received under tests on trajectory c and b ($P = -0,2$) dependence durability from value P appears various at $P < -1$ and $P > -1$ (path b).For its determination realization of additional experiments is required.

By use of energy criterion (17) the divergence of results of account and experiment did not basically exceed 2 times. Received data for combined loading, torsion and the tension - compression of specimens,cutting out under various angles to the axis Z are submitted on fig.6.In the case of torsion calculation W_p on (17) is executed for one of main equaldangerous direction making angle 45^0 with the axis of specimen.

We shall note, that considered above criteria do not permit to describe decrease of cyclic life for steel 2Cr-Ni-Mo-V at loading on a circular trajectory, fig. 7,d, as for a given material the effect of additional cyclic hardening at nonproportional loading was away . It is necessary in this case to take into account influence to formation of cracks type I shear strain and stress.

By use of the energy approach the criterion of fracture can be accepted in a form, similar (2), however included in its parameters will have other physical sense:

$$W = \int_{\Omega} \sigma_j d\varepsilon_{pj} + b \int_{\Omega} \tau_j d\gamma_{pj} \tag{18}$$

Here normal j corresponds direction of maximal main strain or Z - direction (if fracture occur due to stratification); b - a factor, describing influence to appearance the cracks type I the energy of plastic deformation, appropriate shear stress and strain.

We shall note, that the value, determined by ratio (18), is invariant concerning choice direction of axes σ and τ.

If in expressions (5), (6) to take into account as well as in (18) the energy, appropriate to shear component of stress and strain and to use such assumptions, as in equation (16), neglecting distinction in the form stress-strain curves at proportional and nonproportional loading, following strain criterion of fracture can be received:

$$\frac{\sigma_j}{\sigma_{oj}} \Delta\varepsilon_j + b_1 \frac{\tau_j}{\sigma_{oj}} \Delta\gamma_j = C_{pj} N^{m_{pj}} + C_{ej} N^{m_{ej}} \tag{19}$$

The criterion (19) was used for calculation low-cycle fatigue curve for steel 2Cr-Ni-Mo-V (for Z - direction),appropriate to a loading on a circular trajectory, fig. 7,d. As for a given material additional cyclic hardening effect at nonproportional loading was away, the ratio (19) can give a following form:

$$\Delta\varepsilon_j + b_2 \Delta\gamma_j = C_{pj} N^{m_{pj}} + C_{ej} N^{m_{ej}} \tag{20}$$

In considered case of loading Z- specimens most dangerous is Z -direction. In this connection a right part (20) corresponds to the curve tension - compression of Z - specimens. If strain at tension-compression to designate as $\Delta\varepsilon_Z^{o}$, from (20), taking into account, that for a circular trajectory

$$\Delta\gamma = 2\Delta\varepsilon_{\theta Z} = 2/\sqrt{3}\,\Delta\varepsilon_Z$$

we shall receive

$$\Delta\varepsilon_Z = \frac{\Delta\varepsilon_Z^{o}}{1 + b_2 \frac{2}{\sqrt{3}}}$$

Low-cycle fatigue curve calculated this way (for $\Delta\varepsilon_Z$ component) for a circular trajectory (for $b_2 = 0{,}35$) is shown on fig. 3 (dush line). There is shown also calculated on (20) fatigue curve for torsion (dotted line). In last case the most dangerous direction is direction of main strain, and so the right part of (20) corresponds fatigue curve for tension - compression of X - specimens. As follows from fig. 3 agreement of account and experiment is reasonably satisfactory.

Conclusions

1. The low-cycle fatigue resistence of anisotropic steels type 16Cr-9Ni-2Mo and 2Cr-Ni-Mo-V has been examined for strain controlled conditions both proportional and nonproportional loading on specimens wich were cut out in different directions relative axes of anisotropy.

2.For anisotropic materials appearance of additional mechanism of fracture type stratification is posible due to acting normal component stress and strain in direction perpendicular to the plane of rolling.

3.Results for examined materials are shown to confirm the strain and energy approaches, wich account the effects of loading path and anisotropy.

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