ULTIMATE STATE CRITERIA OF STRUCTURAL ALLOYS EXPOSED TO THE ACTION OF ELECTRIC CURRENT PULSES

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ABSTRACT

The ultimate state of any structure or the loss of its load-carrying capacity is characterized by reaching such a state, at which it becomes unsuitable for operation. The ultimate state of a structure, depending on its purpose, is estimated from the generation of excessive strains, crack initiation or opening displacement, violation of the structure integrity, etc. It is the ultimate state mode that determines the choice of the ultimate state criterion, i. e., the condition under which such state sets in. Analysis of the data available in the literature has made it possible to conclude that the occurrence of residual strains is inadmissible for structural elements of superconducting electromagnetic devices. The appearance of such strains should be excluded with the most unfavorable total action of all types of the service factors at maximum possible levels of mechanical loads that occur under both steady-state and abnormal operating conditions of devices. Electromagnetic effects (magnetic fields of high intensity, electric current pulses of high density), which are among the main service factors acting in load-carrying elements of superconducting electromagnetic systems, give rise to the plastic flow of metals at the stresses that are essentially lower than the values of their yield stresses. That is to say, the onset of the ultimate state under the action of electromagnetic effects should be estimated by the stress of the onset of the material plastic flow induced by those effects. In this paper, based on the peculiarities of deformation and fracture of steels and titanium alloys revealed under conditions of the action of the electric current pulses and cryogenic temperatures, the material ultimate state criteria have been formulated and the main principles of the methods for their determination at uniform, nonuniform, and complex stress states as well as with the presence of a crack have been reported.

INTRODUCTION

It has been established reliably by Spitsyn, Okasaki, Strizhalo [1, 2, 3] that an electric current pulse (ECP) passing through a loaded metal leads to a reduction in its resistance to deformation. At the same time, at certain values of the ECP parameters this phenomenon is a result of a specific (electroplastic) action of the electric current. The reduction in the resistance of metallic materials to deformation caused by the electroplastic strain appears on the stress-strain curves in the form of load (stress) jumps. Under appropriate loading conditions (Novogrudsky [4]), the capacity of metals to resist the action of an ECP can be estimated by the magnitude of the stress jump ($\Delta\sigma$). The ECP effect on the kinetics of metal deformation is particularly pronounced at temperatures close to the absolute zero, which is associated with the dependence of the nature of electron-dislocation interaction on temperature (consideration of the mechanisms of electroplastic deformation and physical prerequisites of its formation is outside the scope of this paper. These problems were described in detail in the reviews by Golovin, Pustovalov [5, 6]). At such temperatures, the occurrence of the residual strain in metals resulting from the action of a single electric current pulse can take place at the stress that is considerably lower than the material yield strength. For example, at a temperature of 4.2 K, the effect of an ECP of density 250 MA/m^2 and duration 10^{-2} s triggers the flow of steel 03Kh20N16AG6 at the stress constituting 60% of its yield strength value (Table 1).

As a result of the analysis of the data from the literature on the operation conditions and stress-strain state of load-carrying elements of cryogenic systems for superconducting electromagnetic devices it was found that plastic deformation of the material of which those elements are manufactured is inadmissible. That is, the onset of the ultimate state of those structures should be characterized by the stress corresponding to the beginning of the material plastic deformation, namely, the stress corresponding to the onset of the plastic flow. Then the ultimate state criterion of the loaded elements of superconducting electromagnetic devices is the correspondence of the values of equivalent stresses acting in these elements to the stress of the plastic flow onset in the material from which they are made. In this case, the stress corresponding to the plastic flow onset should be determined under conditions that most closely correspond to the conditions of the material operation in a real structure. In the general case, the yield strength (σ_y) or ($\sigma_{0.2}$) is adopted as the stress corresponding to the onset of the plastic flow (σ_0). At cryogenic temperatures, the stress corresponding to the onset of the discontinuous flow (discontinuous flow limit) can be chosen as such stress. It is evident that in the strength analysis of structural elements of superconducting electromagnetic devices subjected to the action of ECP and cryogenic temperatures during their operation, the stress corresponding to the plastic flow onset induced by the action of an ECP, σ_0^{cur}, should be chosen as the critical one. Then the condition for the ultimate state onset takes the form $\sigma_{eq} = \sigma_0^{\text{cur}}$ and that for strength $\sigma_{eq} \le \sigma_0^{\text{cur}} / n$. Here σ_{eq} is the calculated equivalent stress for the critical zone of the structure and σ_0^{cur} is the stress corresponding to the plastic flow onset under the action of an ECP, i.e., the lowest stress at which the action of a current pulse of specific parameters results in the appearance of a residual strain of a normalized value (by analogy to the 0.2% offset yield stress), and *n* is the safety factor.

Table 1: The values of stresses corresponding to the onset of the plastic flow due to the ECP action (J = 250 MA/м^2, $\tau = 10^{-2}$ s) at a temperature of 4.2 K.

Material	Condition	σ_0^{cur}, MPa		$\sigma_0^{\text{cur}} / \sigma_{0.2}$	
		calculation	experiment	calculation	experiment
Steel with a stable austenite 03Kh20N16AG6	Annealing	951	985	0.77	0.80
	Initial	867	875	0.60	0.61
Metastable steel 12Kh18N10T	Annealing	583	605	0.90	0.93
	Initial	516	525	0.67	0.68
Low-alloy steel 0N9	Initial	858	880	0.69	0.71
Ti alloy PT3V	Initial	792	775	0.83	0.82

The value of σ_0^{cur} can be determined experimentally from a large number of experiments in the medium of liquid helium for given ECP parameters, which is rather inefficient from both scientific and commercial standpoints. As will be shown below, a reliable value of σ_0^{cur} can also be obtained on a basis of a small-scale experiment using the present-day notions about the mechanisms of the ECP action on a loaded metal

The analytical investigations presented below were based on the experimental results obtained from

1) uniaxial tension tests of smooth 5-fold cylindrical specimens with the working section of 4 mm in diameter at temperatures of 77 K and 4.2 K; cylindrical specimens with a circular stress concentrator (the radius at the notch vertex being equal to 0.02 mm, the theoretical stress intensity factor 9.16); half-sine electric current pulses of density 250 MA/m^2 and duration 10^{-2} s were passed along the specimen axis;

2) tests of fatigue precracked compact tension specimens (0.5 CT) at a temperature of 4.2 K. In these tests, the electric current flew around the crack mouth;

3) tests on 1-mm-thick flat disk specimens of diameter 40 mm in hydrostatic tension at a temperature of 77 K with the plane stress state realized using the technique described by Lebedev [7]. The electric current pulses were sent along the disc diameter, and in doing so, the changes in its length and in the length of an orthogonal diameter were measured.

The experiments were performed using steels of various grades (austenitic 03Kh20N16AG6 steel at a temperature of 4.2 K, austenitic-martensitic 12Kh18N10T and 07Kh13N4AG20 steels, and low-alloy ferritic steel 0N9) and titanium alloy PT3V.

EXPERIMENTAL RESULTS.

According to modern notions about the nature of the action of an electric current pulse of high density on the loaded metal, not all pulse energy is spent for heating, a part of the energy is transferred to dislocations stimulating plastic deformation. At temperatures close to absolute zero, when heat-induced vibrations of the lattice are practically absent, such redistribution of the energy must prevail.

Since $\Delta\sigma$ is the response of the metal to the action of the electric current, it was assumed (Strizhalo et al. [8]) that the part of the ECP energy spent for this change in the stress (actually for electroplastic deformation), Q_r, is proportional to the relative change in the stress during the time of the pulse action $\Delta\sigma / \sigma = \lambda$, where σ is the stress value at the instant of the beginning of the ECP action. For an electric current pulse of density J and duration τ, the Q_r value is determined as

$$Q_r = \lambda\rho\int_0^{\tau} J^2(t)dt , \tag{1}$$

where ρ is the resistivity of the material.

The specific work required to deform the specimen by 0.2% of the initial length, $A_{0.2}$, corresponds to

$$A_{0.2} = \int_0^{0.2} \sigma d\varepsilon . \tag{2}$$

The specific energy corresponding to the stress of the beginning of the plastic flow triggered by an ECP, A_0^{cur}, is equal to

$$A_0^{\text{cur}} = A_{0.2} - Q_r . \tag{3}$$

Assuming that Hook's law holds up to σ_0^{cur}, we obtain

$$\sigma_0^{\text{cur}} = (2EA_0^{\text{cur}})^{1/2} ,$$

where E is the elasticity modulus.

With the use of relations (1), (2), and (3), we can write:

$$\sigma_0^{\text{cur}} = \left[2\acute{I} \left(\int_0^{0,2} \sigma d\varepsilon - \lambda\rho \int_0^{\tau} J^2(t)dt \right) \right]^{1/2} . \qquad (4)$$

Comparison of the σ_0^{cur} values calculated using (4) and experimental ones for the steels and titanium alloy studied (see Table 1) reveals that the approach proposed makes it possible to calculate the stress corresponding to the beginning of the plastic flow induced by the ECP action accurately enough (the discrepancy between the values < 5. In this case, to find λ it is sufficient to determine the $\Delta\sigma$ value from an experiment at the stress equal to $\sigma_{0.2}$ of the material.

Since the magnitude of $\Delta\sigma$ depends appreciably on the loading regime, we proposed that it be reduced to a maximum possible value. The latter corresponds to the value registered when a specimen is loaded at a constant sufficiently low strain rate with all other conditions of the experiment being equal. Then the value of λ for the loading regime with a constant loading rate will be determined as (Novogrudsky [6]) $\lambda = 1 - \sqrt{1 - \frac{2E\Delta\varepsilon}{\sigma_{0.2}}}$, and for a regime with a nonconstant loading rate as $\lambda = 1 - \sqrt{1 - \frac{E\Delta\varepsilon}{\sigma_{0.2}}(2 - \frac{\Delta\sigma}{\sigma_{0.2}})}$ Here $\Delta\varepsilon$ and $\Delta\sigma$ are the values of the strain increment and stress jump registered under the action of an ICP in the course of an experiment.

It is advantageous to evaluate the ultimate state of the material in the stress concentrator zones from the limit strain intensity at the concentrator root $e_{i\,\text{lim}}$. Its value is independent of the action of the electric current at the given temperature, and is defined only by the geometrical parameters of the concentrator (Strizhalo et al. [9]): $e_{i\,\text{lim}} = e_{i\,\text{lim}}^{\text{cur}}$. By stimulating the material plastic flow, an ECP facilitates reaching the limit strain at the concentrator root at lower stress levels $\sigma_{i\,\text{lim}}^{\text{cur}}$ than those in the initial state $\sigma_{i\,\text{lim}}$. The relation for determining stresses at which e_i reaches the limiting value due to the ECP action has the form

$$\sigma_{i\,\text{lim}}^{\text{cur}} = A\left(\frac{K_e}{K_e^{\text{cur}}}\right)^m \sigma_{i\,\text{lim}} .$$

Here A is a coefficient that allows for the variation of the rigidity of the stress state in the stress concentrator under the action of the current, K_e and K_e^{cur} are strain concentration coefficients, and m is the strain hardening exponent.

The ultimate state of a body with a crack can be characterized by the crack growth onset. The resistance of a material to the crack growth onset is related to its capacity to irreversibly absorb energy in the course of fracture. The energy absorption takes place in the region surrounding the crack tip. The magnitude of the energy absorbed at fracture depends on the size of the zone wherein the energy dissipation occurs and which is the zone of plastic deformation formed at the crack tip prior to crack initiation. For the material of a preset thickness, the critical value of the plastic deformation zone radius r_{cr} (the radius value at which the crack growth onset occurs) is a constant value, which makes it possible to use it as the characteristic of the ultimate state. The condition for the onset of the ultimate state has the form

$$r = r_{cr} = \frac{1}{k}\left(K_c / \sigma_{\text{y}}\right)^2 , \qquad (5)$$

where r is the current value of the plastic zone radius; K_c is the critical stress intensity factor; k is the coefficient that takes into account the stress state mode at the crack tip.

Since the ECP only stimulates the development of plastic deformation, the quantity r_{cr} can be considered as the characteristic of the ultimate state under the action of the electric current as well:

$$r^{\text{cur}} = r_{cr}^{\text{cur}} = \frac{1}{k}\left(K_c^{\text{cur}} / \sigma_{cr}^{\text{cur}}\right)^2 = r_{cr}\,, \tag{6}$$

where r^{cur} and r_{cr}^{cur} are the current and critical values of the plastic zone radius under the action of an ECP, respectively; K_c^{cur} is the critical stress intensity factor under the action of an ECP; σ_{cr}^{cur} is the stress at which the yielding condition due to the action of an ECP is fulfilled on the plastic zone contour. Its value is determined with the aid of Eq. (4). The use of relationship (6) presents a possibility of predicting the value of the stress intensity factor under the action of an ECP, K_c^{cur}, from the known value of K_c for the material in the initial state:

$$K_c^{\text{cur}} = \sqrt{2Ekr_{cr}\left(\int_0^{\varepsilon_1} \sigma d\varepsilon - \lambda\rho\int_0^{\tau} J^2(t)dt\right)}\,. \tag{7}$$

Here ε_1 is the strain corresponding to τ_{cr}. As an example we determine the value of the critical stress intensity factor for steel 0N9 under the action of an electric current pulse at the temperature of liquid helium. At this temperature, 0.5 CT specimens of this steel without the action of the electric current fracture under plane strain conditions. With the use of the experimental K_{IC} value obtained at a temperature of 4.2 K, the value of r_{cr} was calculated from Eq. (5), and then using relationship (7), we obtained $K_{\text{IC}}^{\text{cur}}$ = 55 MPa√m. The experimentally determined value of $K_{\text{IC}}^{\text{cur}}$ obtained under similar conditions is 57 MPa √m.

The onset of yielding (ultimate state) of cold-plastic materials (exhibiting high plasticity at cryogenic temperatures) at a complex stress state at cryogenic temperatures is described rather accurately by the von Mises criterion:

$$\sigma_{eq} = \left[\frac{1}{2}(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2\right]^{1/2} = \sigma_{\text{y}}\,.$$

Under the action of an ECP the condition of the onset of yielding will take the form

$$\sigma_{eq}^{\text{cur}} = \sigma_0^{\text{cur}}\,.$$

In the case of equiaxial tension of a disc specimen $\sigma_1 = \sigma_2 = \sigma_r$ and $\sigma_3 = 0$ (here σ_r is the stress acting along the disk specimen radius), hence: $\sigma_{eq} = \sigma_r$ and $\sigma_{eq}^{\text{cur}} = \sigma_r^{\text{cur}}$. In other words, in the given case of the plane stress state, the material ultimate state occurs when the radial stress values reach the value of the yield strength. Under the action of an ECP, the ultimate state of the material occurs when the σ_r^{cur} value reaches that of the stress corresponding to the plastic flow onset σ_0^{cur} determined experimentally or with the help of relation (4). A comparison we made between the magnitudes of σ_r^{cur} corresponding to the yielding onset ($\Delta\varepsilon =$ 0.2%) obtained in testing of disc specimens of steel 07Kh13N4AG20 at 77 K and those of σ_0^{cur} determined in uniaxial tension has shown that their difference does not exceed 3%.

In the case of anisotropy of the mechanical characteristics of the material, the magnitude of σ_0^{cur} should be determined in the direction of the maximum influence of the ECP. This direction generally coincides with that of the maximum value of the material electrical resistance.

CONCLUSIONS

The ultimate state criteria for structural alloys subjected to the action of electric current pulses and cryogenic temperatures under conditions of linear uniform, nonuniform, and complex stress states and with a crack present have been proposed and substantiated.

The parameters such as the stress of the onset of the plastic flow induced by an electric current pulse, the strain intensity at the notch root, the critical value of the plastic zone radius at the crack tip, and the stress intensity at a complex stress state have been proposed to be used as the characteristics determining the onset of the ultimate state of metallic materials under the above conditions.

A comparison of the experimental and calculated values of the above parameters in the limiting cases has been made and their good agreement has been shown.

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