STANDARDIZATION OF THE STRENGTH OF METALS UNDER CONDITIONS OF LOW-TEMPERATURE INSTABILITY OF PLASTIC DEFORMATION AND THE ACTION OF STRONG MAGNETIC FIELDS

E. V. Vorob'ev and V. A. Strizhalo

UDC 539.43

We propose an approach to determination of allowable stresses by a static-strength criterion for materials of structures that operate at very low temperatures \((T \leq 20 \text{ K})\). This approach takes into account the qualitative change in the nature of deformation of the material, which has a significant effect on the mechanical characteristics and the specific work of deformation. The choice of critical stresses for these conditions is substantiated. The calculations are performed by introducing corrections for low-temperature hardening of the material in the presence of the intermittent-flow effect. We discuss the possibility of taking into account the influence of strong magnetic fields on the magnitude of allowable stresses.

Introduction. It is known that when the critical state of a structure under static loading is evaluated by a conventional approach, equivalent stresses are compared with allowable ones obtained with regard for the magnitude of critical stresses, i.e., the yield strength \(\sigma_Y (\sigma_{0.2})\) or ultimate strength \(\sigma_u\) and safety factors \((n_Y \text{ and } n_u, \text{ respectively})\). Information about the stress state of structural elements that is needed for determination of equivalent stresses can be obtained by fairly simple calculations, while the problem of choosing reliable values of allowable stresses for certain classes of structures is still to be solved. For instance, one encounters considerable difficulties in normalizing the strength of cryogenic-engineering structures \([1-3]\) because the extent to which the structural strength of materials at low temperatures decrease with respect to the strength of standard specimens is much greater than under normal conditions. Also, for temperatures close to absolute zero it is very difficult, if possible, to choose a critical-stress magnitude because of the change in deformation behavior of metallic materials.

Making a decision on allowable stresses for superconducting magnetic systems of corresponding power units is complicated by the requirement of minimizing the dimensions of load-bearing components (coil spools, etc.) while providing the best use of the safety margin of the material under the action of powerful magnetic fields and neutron flux.

With consideration of the foregoing, we discuss here possible approaches to standardization of strength at temperatures \(T \leq 20 \text{ K}\), which are characterized by special deformation behavior of metallic materials. This temperature range includes the boiling points of liquid helium (4.2 K) and hydrogen (20 K), which determine the operating temperature of a number of modern cryogenic systems.

Low-Temperature Hardening and Methods of Taking It into Account. The main safety margin of components of cryogenic structures can be thought to include low-temperature hardening of the corresponding structural materials. Cryogenic engineering uses mainly austenitic steels and alloys based on Ti, Al, Ni, and Cu that have no distinct cold-brittleness threshold over the entire low-temperature range and, when cooled to 4.2 K, exhibit an increase in the yield strength by 200% or more. Appropriate methods of taking into account low-temperature hardening in determining allowable stresses for such conditions are stipulated by the standards and regulations \([4, 5]\). According to \([4]\), for cold-ductile materials, just as at room temperature, the lower of the following values is taken as the allowable stress:

\[
[\sigma^T] = \min\left(\sigma^T_{0.2} / n_Y; \sigma^T_u / n_u\right)
\]
where \( \sigma_{0.2}^T \) and \( \sigma_u^T \) are the values of the critical stresses for the given low or cryogenic temperature, while the safety factors are taken for normal conditions (293 ± 10 K). It is obvious that in this case the calculations involve quantities that are incommensurable in temperature, while no correction is made. In view of the above difference between the structural and technical strength, this can lead to an unjustified overestimate of allowable stresses in the region of low temperatures.

The standard [5], which was substantiated in [6], takes into account in a comprehensive way the special features of the influence of cryogenic temperatures on the strength and stress-strain behavior of materials as well as the influence of design and technological factors. The standard [7], too, provides the possibility of standardization of the strength of materials at low temperatures. Also, the energy-based method proposed in [8] allows one to utilize low-temperature hardening. As distinct from the recommendations of [4], the methods described in [5, 7, 8] take into account, in one way or another, the energy-absorbing ability of materials, thus permitting a more flexible approach to the determination of allowable stresses to be found.

**Region of Instability of Plastic Deformation of Metals.** The above approaches to standardization of strength take no account of the special features of deformation of metallic materials at \( T \leq 20 \) K, i.e., the so-called effect of low-temperature intermittent flow (IF) or stepwise deformation, which is recorded graphically in the form of sawtooth deformation curves. At higher temperatures, for most metallic materials the deformation curves are monotonic and plastic deformation is distributed uniformly in the bulk of the specimen, while in the temperature range under study, as a result of periodic loss of thermal and plastic stability deformation proceeds at a higher rate and is local, which causes intense thermal flashes in the flow zone [9–12]. An abrupt transition from elastic deformation to a localized dramatic flow under operating conditions can be considered as a stepwise deterioration of the strength of the structural element. This can lead to failure of the element because of excessive deformation or fracture that occurs during the jump due to release of accumulated elastic energy and concurrent dynamic effects [13–15].

The IF effect is realized when the following criteria are fulfilled: the adiabatic criterion \( c / c_k \leq 1 \), the deformation-force criterion \( \Theta / \Theta_k \leq 1 \), and the force criterion \( \sigma / \sigma_k \geq 1 \) [9, 12, 13], where \( c_k, \Theta_k, \) and \( \sigma_k \) are the critical values of the specific (volumetric) heat capacity, strain-hardening coefficient, and stress, respectively. Their values are interrelated: as the test temperature (and thus the value of \( c_k \)) is raised, the point of appearance of IF in the tensile stress-strain diagram shifts to the right, i.e., a lower value of \( \Theta_k \) and a higher value of \( \sigma_k \) correspond to a higher value of \( c_k \) (Fig. 1a, b). Relations between these parameters can be found from the expressions

\[
\beta_c \sigma_0 \varepsilon_c = \int_{T_0}^{T_0+\Delta T} c(T)dT, \tag{1}
\]

\[
\varepsilon_c = \frac{\Delta T k_f}{\Theta + K}. \tag{2}
\]

The first expression is the equation of energy balance of the stepwise deformation, while the second gives the value of the strain increment \( \varepsilon_c \) [12]. Here, \( \beta_c \) is the coefficient of conversion of the work of plastic deformation into heat, \( \sigma_0 \) is the stress at the beginning of the jump, \( \Delta T \) is the temperature increment in the flow zone, \( k_f \) is the thermal-softening coefficient, \( K \) is the effective elastic modulus of the specimen-machinery system, which is proportional to the stiffness of this system. The quantity \( \Delta T \) is the determining parameter, i.e., IF starts when \( \Delta T \) reaches some critical value [16] (in the region of developed IF the value of \( \Delta T \) for aluminum is about 60 K [10] while for high-strength materials it ranges up to 180 K [12]). And as follows from expressions (1) and (2), the higher the flow stress and the smaller the strain-hardening coefficient, the larger the temperature increment for a given initial value of the heat capacity. (It should be mentioned that fulfillment of the adiabatic criterion at a sufficiently low temperature accordingly requires fulfillment of the relationship \( \dot{\varepsilon} / \dot{\varepsilon}_k \leq 1 \), i.e., the kinetic criterion [12, 17], where \( \dot{\varepsilon}_k \) is the critical value of the strain rate.)

In the limit where \( c_k \) and \( \Theta_k \) tend to zero, we obtain \( \sigma_k \to \sigma_y \), while when these quantities approach their maximum values, we have \( \sigma_k \to S \), where \( S \) is the maximum true stress. In the initial stage of elastoplastic deformation the value of the strain-hardening coefficient of the material decreases drastically [13] so that the critical stress can be close to the conventional yield stress, e.g., \( \sigma_{0.2} \), as is the case with a number of austenitic steels (03Kh20N16AG6, 460