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New types of limit states of structural alloys related to the realization of the low temperature discontinuous yielding effect

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1. Introduction

Advances of recent decades in some branches of technology have called for extending the range of working temperatures almost to absolute zero. This can be explained by the progresses in power engineering, rocketry, transport sector, medical engineering, and research facilities for physics studies. The application of cryogenic superconducting magnetic systems cooled by liquid helium allows the creation of mighty and economical energy generating equipment, electric energy storage devices, elementary particle accelerators, spectrometers, fusion reactors, etc. The service conditions for the mechanical elements of such systems are distinguished by a particular extremity due to the combined action of high mechanical stresses, strong electromagnetic and other physical fields, and extremely low temperatures. But in deep cooling to temperatures below 30 K, where the boiling points of liquid hydrogen and helium (20 and 4.2 K, respectively) lie, a qualitative change in the mechanism of deformation of metallic materials takes place – the deformation process becomes unstable and discontinuous [1]. This effect, called low temperature discontinuous yielding or jumplike deformation, is recorded as saw-tooth stress strain curves in which the amplitude of stress jumps can reach 60% of the initial level [2].

The appearance and behavior of the discontinuous yielding of a given material are known to depend significantly on the loading conditions – strain rate and thermal-physical characteristics of the cooling medium; the rigidity of the loading system and the loading regime; and also the design and manufacturing factors – the presence of initial strains and stress concentrations, size and shape of the deformed object, etc. An abrupt change from the stage of elastic deformation to the jumplike localized deformation, typical for high-strength structural alloys, should be considered as a jumplike decrease in the loading resistance or a sudden loss of strength of a structural member, which can lead to failure due to the appearance of excessive strains or fracture. The probability of this failure increases in the case of the presence of an initial strain in the material, a stress concentration, the action of energy pulses of different nature, a large quantity of the stored elastic energy and a high loading rate [3]. However, the available methods of standardizing the strength of structures operated at the liquid helium temperature do not take into account the possible development of catastrophic plastic yielding [4-6].

To account for the nonsteady-state nature of the deformation of structural alloys, the methodology of strength analysis for the corresponding structures should be based on criterial estimates of the material limit states that occur during the appearance and evolution of low-temperature jumplike yielding. The first attempt to tackle this problem was made in [7]. The object of the present paper is to systematize and classify the discovered limit states and obtained criteria [3], which can be done by considering the multitude of factors governing the manifestation of discontinuous yielding, its stages, and its adiabatic, non isothermal, and non uniform nature.

2. Limit states and criteria

The comprehensive study on the effect of elastic, inertial, and kinetic characteristics of the loading system and other factors, including the design and manufacturing ones, on the plastic deformation behavior, strength and fracture of specimens of alloys under conditions of static and quasistatic tension in liquid helium medium was conducted with regard for the staged nature of the strain accumulation process, namely, the precritical stage of uniform deformation, the loss of stability in the deformation process, the strain jump itself, and the stage of nonadiabatic deformation immediately following the strain jump. This allowed us to answer the following questions:

- will the discontinuous yielding phenomenon take place under specific loading conditions;
- is it possible that excessive strains will appear or fracture will occur during a strain jump or after its cessation;
- how do the parameters of discontinuous yielding and conventional mechanical characteristics of a material change under the influence of different factors.

The solution of the last problem provided developing recommendations as to improving the standard method of static tensile testing of metals at temperatures below 30 K and the other two problems are directly related to criterial assessment of the phenomenon. Such an assessment involves deriving a system of inequalities defining the conditions where the plastic strain accumulation will become unstable if discontinuous yielding starts after the stage of gradual uniform plastic deformation or the conditions where the limit states will be attained if the strain jump immediately follows the elastic deformation stage. In either case, it is necessary that the main criterion, the criterion of thermal instability or "adiabatic deformation" [1], be valid. To this end, the heat capacity of a metal (and, accordingly, the temperature) should be no higher than some critical value.

In case the phenomenon evolves in the first way, the above system can be generally presented as $c/c_c \leq 1$; $T/T_c \leq 1$; $\dot{\varepsilon}/\dot{\varepsilon}_c \leq 1$; $\theta/\theta_c \leq 1$; $\sigma/\sigma_c \leq 1$; $\varepsilon/\varepsilon_c \leq 1$ [8]. Here c is the volumetric heat capacity; T is the temperature; ε and $\dot{\varepsilon}$ are the plastic component of strain and its rate; θ is the strain hardening modulus; σ is the stress, and the symbol c denotes the corresponding critical values. In order to obtain a complex criterion, it is necessary to define the main parameters. If the strain rate is sufficiently low, it has practically no effect on the specimen temperature. The relationship between the thermal physical parameters is described by the temperature dependence of the thermal capacity. The appearance of jumps on the stress strain curve corresponds to a certain point, whose coordinates, the true stress σ_c and true strain ε_c, are the critical quantities in the force and strain criteria. At the same point, the strain hardening modulus decreases down to the critical value θ_c on attaining which the thermal effects that initiate and stimulate discontinuous yielding are no longer suppressed. The relationship between the mechanical parameters is established with the help of the equation of state, and their critical values can be determined from one of them obtained experimentally at a given temperature, namely, the discontinuous yield strength of the first kind σ_{dy_I} whose true value is equal to σ_{c_0}.

It is evident that the critical values of the thermophysical and mechanical parameters are also interrelated: with an increase in temperature, the point of the appearance of jumps on the curve is shifted to the right, i.e., greater values of σ_c and ε_c correspond to greater values of c_c and T_c.

Thus, the complex criterion that determines the condition for the realization of the limiting state of the loss of plastic deformation process stability can include only two governing parameters and can be considered as a thermal-and-force criterion $\sigma/\sigma_c(T) \geq 1$. A corresponding criterial relationship was formulated in the form [8]

$$\sigma_c \beta_c = \sigma_{c_0} \beta_0 \rho \left(k_1 T + k_2 T^3\right) \tag{1}$$

where ρ is the material density; k_1 and k_2 are the coefficients of the heat capacity temperature dependence; c_0 is the initial value of heat capacity; $\beta_0 = \beta(\sigma_{c_0})$ and $\beta_c = \beta(\sigma_c)$ are the energy transformation coefficients calculated on the basis of the obtained analytical dependence [9]

$$\beta = \left(1 + k_\beta \theta / \sigma\right)^{-1} \tag{2}$$

where $k_\beta \approx 0.05$, and the adopted equation of state, e.g., of the form

$$\sigma = \sigma_y + B\varepsilon^m \tag{3}$$

where σ_y is the yield strength and B and m are constants. For the hardening law (3) we have $\theta = mB^{1/m} \Big/ \left(\sigma - \sigma_y\right)^{\frac{1-m}{m}}$ and $m = \sigma_b \varepsilon_b / \left(\sigma_b - \sigma_y\right)$, where σ_b and ε_b are the true stress and strain that correspond to the ultimate strength, σ_u, and equation (2) is transformed as

$$\beta(\sigma) = \left\{1 + k_\beta \sigma_b \left(\sigma_b - \sigma_y\right)^{\frac{1-m}{m}} / \left[\sigma\left(\sigma - \sigma_y\right)^{\frac{1-m}{m}}\right]\right\}^{-1} \tag{4}$$

Relationship (1) includes only two material constants, namely, the heat capacity and discontinuous yield strength of the first kind. The possibility of using this complex criterion is shown by the example of the grade AMg6 aluminum alloy and grade 03Kh20N16AG6 steel that differ considerably in their strength characteristics. For those materials, the values of $T_{c_{\max}}$ were obtained equal to 9 and 27 K, respectively, and this was verified experimentally. Fig. 1 presents the calculated temperature dependences of the critical stresses and the instability regions in the plane of the parameters σ_c and T_c.

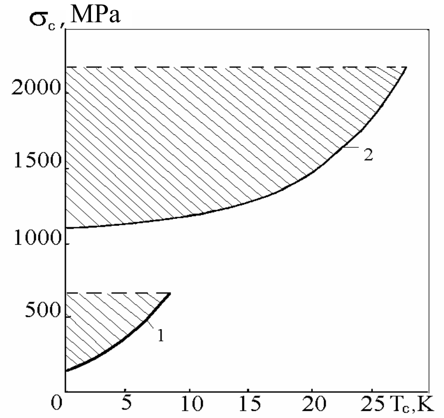

Fig. 1 Temperature dependences of the critical stress and instability regions for grade AMg6 alloy (*1*) and grade 03Kh20N16AG6 steel (*2*)

The criterion considered was obtained on the assumption that the specimen temperature T does not practically differ from the nominal temperature T_0 that corresponds to the boiling point of the cooling agent since the strain rate is sufficiently low. But otherwise, it can influence the deformation behavior at all the stages of evolution of the discontinuous yielding effect, as a consequence of which a number of kinetic criteria can be formulated. In particular, at a subcritical stage of elastoplastic deformation, an essential increase in the specimen temperature can occur due to the work of deformation that defines the heat release intensity $\beta\sigma\dot{\varepsilon}$. The relationship below, which relates the increment in the specimen temperature ΔT_w to the strain rate [10], is derived from the energy balance equation set up with the allowance for heat transfer with the environment at the onset of heat balance ($dT/dt = 0$)

$$\Delta T_w = \beta\sigma\dot{\varepsilon} V_w / qS \tag{5}$$

here q is the coefficient of heat transfer depending on the cooling agent boiling conditions; S is the area of the specimen gage length; V_w is its volume. If the $T = T_0 + \Delta T_w$ value becomes equal to the temperature $T_{c_{\max}}$, which is critical for the existence of the discontinuous yielding effect, the corresponding value of $\dot{\varepsilon} = \dot{\varepsilon}_{c_2}$ is critical. For standard specimens (3 mm in diameter) of austenitic steels and titanium alloys and liquid helium medium, the calculation gives $\dot{\varepsilon}_{c_2} \approx (4.0\ldots7.7)\cdot10^{-3}$ s^{-1}, with this value being the lower, the higher the strength of the material. As shown by the experiments, the effect of discontinuous yielding in this range is suppressed completely and the stress strain curves become smooth. This causes considerable changes in the mechanical characteristics of the materials: the ultimate strengths decrease by ~ 20% and the relative elongation decreases by a factor of 2, whereas the yield strengths remain practically constant. Similar changes in the deformation behavior and in the mechanical characteristics also occur in the case of the stress controlled loading, when the critical value of the loading rate $\dot{\sigma}_{c_2}$, which can be approximately defined as $\dot{\sigma}_{c_2} = \theta\dot{\varepsilon}_{c_2}$ assuming the θ value to be constant, is exceeded.

With the use of Eq. (5) we can calculate the limiting strain rate, $\dot{\varepsilon}_{c_1}$, at which $\Delta T_w \le 1$ K and, in the medium of liquid helium, the regime of the most intense heat exchange is retained. This guarantees for the alloys of cryogenic engineering the possibility of realization of the discontinuous yielding effect. This relation was used in the proposed approach to normalize the conditions of standard tensile tests of metals at temperatures down to 4.2 K. For specimens of the diameter up to 5 mm, normative strain rate should be $\dot{\varepsilon}_n \le 2\cdot10^{-3}$ s^{-1}. The influence of the size-scale effect on the magnitude of critical strain rate can be determined if the following substitution is made in Eq. (5): $V_w/S = R/2$, where R is the specimen radius.

It should be noted that on the basis of Eqs. (1) and (5) and the condition of retaining the heat exchange regime, with q being constant, it is possible to formulate a three-parameter criterion of plastic strain instability by substituting in (1) the specimen temperature as $T = T_0 + \Delta T_w$.This criterion describes the region of instability in the space of parameters $\sigma, \dot{\varepsilon}$ and R.

If the subcritical stage of plastic strain accumulation is absent and a jump immediately follows the elastic deformation, the limiting state of jumplike reduction in the loading resistance (the evolution of jumplike deformation) is realized. This state sets in when the upper critical stress (the discontinuous yield strength of the second kind) $\sigma_0(\sigma_{dy_{II}})$ is reached, Fig. 2*a*, i.e., at $\sigma/\sigma_0 \ge 1$, and ceases to exist when the critical stress decreases to the lower limit

$$\sigma_{lc} = \sigma_0 - \delta\sigma \qquad (6)$$

where $\delta\sigma$ is the stress jump amplitude.

The onset of the corresponding limiting state can be determined not only by a transition to discontinuous yielding but also by the strain evolution in the course of the jump itself. For this reason, the problem was set and solved aimed at obtaining an adequate mathematical model for this process that would make it possible to describe the jump kinetics and evaluate its strain, rate, and force parameters taking into account the loading system properties, specifically, to calculate the magnitude of the jumplike strain ε_j [11]. The condition for attaining the limiting state of reaching the excessive strain or fracture is the relation

$$\varepsilon_j / \varepsilon_{cr} \ge 1 \qquad (7)$$

where the critical value ε_{cr} is equal to the allowable, ε_t, or fracture, ε_d, one, respectively.

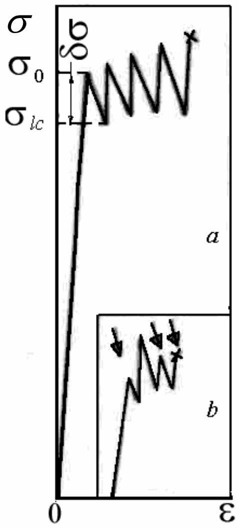

Fig. 2 Schematic presentation of the stress-strain diagrams for specimens of austenitic 03Kh20N16AG6 steel at a temperature of 4.2 K

Formal condition (7) is attained at a certain correlation of the loading system rigidity C and the strain hardening modulus of the material, which define, respectively, the magnitudes of the available elastic energy and the work of deformation at a given σ_0 value. The fracture condition can be presented as

$$C/C_c \le 1 \qquad (8)$$

where, the critical value $C_c = C(\theta)$. Considering that the part of the available elastic energy expended for the specific work of jumplike deformation is $\Delta W = \left(P_0^2 - P_{lc}^2\right)/2CV$, where $P_0 = \sigma_0 A,\ P_{lc} = \sigma_{lc} A$ and $V = lA$, A is the specimen cross-section area, l is the length of the yielding zone, and assuming $l \sim R,\ \theta = const$ and $\beta = const$, in the first approximation we obtain an equation that relates the aforementioned parameters in the form

$$C_c = k_C\left(\sigma_0^2 - \sigma_{lc}^2\right)R / \left[\varepsilon_d\left(\sigma_0 + 0.5\varepsilon_d\theta\right)\right] \qquad (9)$$

here k_C is the dimensionless coefficient of proportionality. It should be noted that the $\delta\sigma$ value is practically independent on the loading system rigidity. That is why, with account of (6), its critical value, at which fracture by adiabatic shift occurs in the course of a jump, is determined by the θ and ε_d values for given σ_0 and R. For approximate calculations, the ε_d value can be set equal to the relative specimen elongation after rupture.

The strain rate or loading rate is another factor that occurs in the system being continuously loaded and, unlike the rigidity, can influence the behavior of discontinuous deformation at all stages of its development. In the considered case of an abrupt appearance of discontinuous yielding, this factor doesn't restrict the possibility of the strain jump occurrence but can essentially influence the strain magnitude and kinetics. To study this case, a mathematical model for the system under continuous loading was constructed [11]. Investigation of this model performed using specimens of grade 03Kh20N16AG6 steel as an example shows that an increase in the total jumplike strain value by more than 5% occurs at the strain rates in excess of $30\cdot10^{-3}$ s^{-1} only. Considering that the standard strain rate does not exceed $1.7\cdot10^{-3}$ s^{-1}, under conditions of static loading the specimen-machine system can be considered as such for which the process of loading has been interrupted and an appropriate (simpler) model can be used [11].

After the cessation of the jump, the influence of continuous loading can become essential even at relatively small $\dot{\varepsilon}$ values as further evolution of the deformation process, which is not adiabatic anymore, is determined by the ratio of the intensity of the material hardening due to straining and cooling and the intensity of geometrical softening in the neck formed. Here, we have the second kinetic fracture criterion in the form

$$\dot{\varepsilon}/\dot{\varepsilon}_d \geq 1 \qquad (10)$$

where $\varepsilon_d = k_T \nu/(\sigma_{lc} - \theta)$ is the third critical strain rate, k_T is thermal hardening coefficient, and ν is the cooling rate determined by the specimen shape and size and the characteristics of the cooling agent. It is evident that the following inequality is an additional condition of fracture

$$\sigma_{lc}/\theta < 1 \qquad (11)$$

and the $\theta = \sigma_{lc}$ value is a critical one. In typical cases, $\dot{\varepsilon}_d$ is of the order of 10^{-2} s^{-1}.

3. Conclusions

Having analyzed different mechanical behavior of metallic materials under conditions of deep cooling and discontinuous yielding, we can distinguish the following limit states of the material and the appropriate criterial characteristics.

1. Loss of the elasto-plastic deformation stability due to a qualitative change in its mechanism. A basic condition for this is the reduction of temperature and accordingly of the heat capacity below the critical one. In this connection, there is one kinetic criterion (I), which ensures a sufficiently low heat release intensity at the subcritical stage of uniform plastic deformation, and another one (II), which is responsible for a complete suppression of the discontinuous yielding effect. The critical quantities mentioned above are determined using Eq. (5). A direct transition to jumplike deformation characterizes the discontinuous yield strength of the first kind. The critical values of strain and strain hardening modulus correspond this yield strength.

2. An abrupt transition from the stage of elastic deformation to the jumplike localized plastic yielding. It takes place when the discontinuous yield strength of the second kind or the upper critical stress is attained. According to (6), a jumplike decrease in the stress $\delta\sigma$ characterizes the lower critical stress at which the jump is impossible.

3. Attainment of the excessive strain including the one resulting in fracture during the jump by the adiabatic shear mechanism in a system for which the loading process was interrupted. It is attained if the critical value of the stored elastic energy determined by the loading system rigidity is exceeded (ratios (7), (8), (9)).

4. Transition to the nonadiabatic localized plastic deformation, which can occur immediately after the cessation of the strain jump in a system under continuous loading at a sufficiently high strain rate. In this case, further load decrease and fracture take place after the third critical strain rate and the corresponding critical value of hardening modulus have been reached (ratios (10), (11)).

The determination of allowable stress is one of the main elements of structural strength calculations. Under conditions of nonsteady-state deformation at temperatures below 30 K, this is complicated by the variability of dangerous stresses for which the offset yield strength and ultimate strength are traditionally used. An important practical question arises as to the choice of a measure of the material strength under the given unusual conditions.

The ultimate strength is attained under conditions of nonisothermal and nonuniform deformation and at the same time heavily depends on the loading conditions. The variability is also characteristic of the critical stress σ_0, i.e., the discontinuous yield strength of the second kind (Fig. 2, a) – it can be greater or smaller depending on the vibration level in the setup and the presence of other external actions. A “premature” jump can be initiated by a pulse of energy (Fig. 2, b) – thermal, electromagnetic, mechanical (due to a load pulse, etc.). As the experiments conducted showed, the stress σ_0 is the upper boundary of dangerous (unallowable) stresses and the “premature” jump at the lower critical stress σ_{lc} becomes impossible. Within the framework of this concept, σ_{lc} acquires a specific meaning of the boundary of unconditionally stable (safe) material states. Precisely this stress is taken as a measure of strength in the proposed method of determining allowable stresses for the nonsteady-state deformation conditions considered.

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E. Vorobjev

NAUJOS KONSTRUKCINIŲ LYDINIŲ RIBINĖS BŪSENOS SUSIJUSIOS SU TRŪKIOJO TAKUMO EFEKTO REALIZACIJA ŽEMOJE TEMPERATŪROJE

Reziumė

Susistemintos ir suklasifikuotos naujų rūšių ribinės būsenos ir atitinkamos kritinės charakteristikos, gautos realizuojant žematemperatūrio trūkiojo takumo efektą, atsižvelgiant į jo daugiafaktoriškumą ir stadijiškumą. Parodyta, kad medžiagos stiprumo įverčiu gali būti mažiausias kritinis įtempis, atitinkantis žemiausią šuolio lygį.

Ye. Vorob'ev

NEW TYPES OF LIMIT STATES OF STRUCTURAL ALLOYS RELATED TO THE REALIZATION OF THE LOW TEMPERATURE DISCONTINUOUS YIELDING EFFECT

Summary

New limit states attained during the realization of the low temperature discontinuous yielding effect and the corresponding criterial characteristics have been systematized and classified taking into account many factors governing the manifestation of this phenomenon and its staged nature. It has been shown that the lower critical stress corresponding to the lower peak of the jump can be adopted as a measure of the material strength.

Е. Воробьев

НОВЫЕ ВИДЫ ПРЕДЕЛЬНЫХ СОСТОЯНИЙ КОНСТРУКЦИОННЫХ СПЛАВОВ, СВЯЗАННЫЕ С РЕАЛИЗАЦИЕЙ ЭФФЕКТА НИЗКОТЕМПЕРАТУРНОЙ ПРЕРЫВИСТОЙ ТЕКУЧЕСТИ

Резюме

Дается систематизация и классификация новых видов предельных состояний и соответствующих критериальных характеристик, наступающих при реализации эффекта низкотемпературной прерывистой текучести с учетом его многофакторности и стадийности. Показано, что в качестве меры прочности материала может быть принята величина нижнего критического напряжения, соответствующая уровню нижнего пика скачка.

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