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Assessment and accounting for extreme impacts for validation of strength and service life of highly loaded machines and structures

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Abstract The paper presents four groups of problems that are critical for assessment and validation of strength and service life of technical systems operating under extreme loading conditions: (1) developing constitutive equations valid in wide ranges of strains, strain rates and temperatures; (2) analysis of the kinetics of local states of stresses and strains in notch zones for elastic, limited elastoplastic and severe plastic strains; (3) justified selection of the criterion of ultimate damage and fracture; (4) assessment of the local stresses and strains at the crack tip according to the formulation of the nonlinear fracture mechanics. The results of studies of the problems of deformation, damage accumulation and fracture under extreme coupled thermomeachanical loading conditions that are relevant for highly loaded machines and structures employed in nuclear and thermonuclear power engineering as well as in aircraft, rocket and space engineering industries are described

Keywords: coupled thermomeachanical loading; constitutive equations; highly loaded structures; thermonuclear engineering

1. Introduction

In the historical retrospective the development of basic and applied research in the field of mechanics of deformable solids was focused on a step by step study of the governing dependencies describing increasingly complex processes of deformation, damage accumulation and fracture. Advanced basic and applied study of the problems of deformation and fracture of materials in connection with the achievement of coupled thermo-mechanical limit states requires special formulation aimed at assessment of various combined regimes of both

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external and internal thermomechanical loading at nano-, micro-, meso-, and macro levels in the application to fracture mechanics and structural integrity.

Nomenclature

A	mechanical energy
d	accumulated damage
C_p	specific heat capacity of the material
c	is volumetric heat capacity
D_{ec}	plasticity reduction factor at the notch
e	strain
$\overline{e}$	normalized strain
e_c	critical strain
e_f	fracture strain
e_n	nominal strain
e_p	plastic strain
e_{ij}^p	components of the plastic strain tensor
e_y	yield strain
$\overline{e}_{\max c}$	normalized maximum local strains in notch zones
E	energy absorbed by the material
$\dot{e}$	strain rate
F	force
I_c	yield stress reduction factor due to stress triaxiality at the notch
t	temperature
k_Q	load growth factor
l	size of the crack (defect)
l_0	initial length of the deformable solid
l_f	final length of the deformable solid
m	strain hardening exponent
N	number of loading cycles
N_c	numbers of cycles to failure
K_σ	stress concentration factor
K_e	strain concentration factor
K_t	theoretical stress concentration factor
$\overline{K}_{Ie}$	normalized strain intensity factor
$\overline{K}_I$	normalized stress intensity factor
$\overline{\sigma}_n$	normalized nominal stress
P	probability of failure
Q	external and internal impacts
Q_e	energy dissipated in the form of heat
$q_{i,j}$	divergence of the heat flux vector and dots denote time derivatives
R	risk
S	characteristic of resistance to impacts
T	absolute temperature (K)
U	expected losses,
α	parameter of state
α_T	linear temperature expansion coefficient
β_T	volumetric thermal expansion coefficient
σ_{-1}	fatigue limit
σ_c	critical stress
$\sigma_{\max c}$	maximum local stress at the notch root

$\overline{\sigma}_{\max c}$	normalized maximum local stresses in notch zones
σ_n	nominal stress
σ_u	ultimate strength
σ_y	yield stress
$\overline{\sigma}$	normalized stress
ρ	material density
ΔT	decrease in temperature in K
η	factor characterizing the fraction of energy (power)
τ	time
T	absolute temperature in degrees K;
σ_{ij}	components of the stress tensor
η	factor characterizing the fraction of energy (power)
δ_{ij}	Kronecker symbol

The solution of basic and applied problems of the mechanics of deformable solids was mainly associated with the development of traditional types of machines and technologies in construction industry, mechanical and power engineering. Rapid development of modern branches of technology (jet, nuclear, thermonuclear, rocket and space technology, nuclear surface and submarine fleets, etc.) has radically changed the setting of tasks in theoretical and applied mechanics. The traditional mechanical, isothermal, seismic, aerohydrodynamic loading regimes were supplemented by extreme non-isothermal (from -269 to + 2000^{0}C), electromagnetic (up to 20 Tesla) loadings as well as radiation (up to 10^{22} neutron/sm^2), laser, ion-plasma, hydrogen with high pressures, liquid metal impacts. Under these conditions an analysis of the ultimate emergency and catastrophic states was added to the analysis of the design bases states of facilities (Makhutov, 2017; Makhutov, 2008).

2. Governing equations and their parameters

The formation of constitutive equations that determine the relationships between true stresses and strains in the wide strain ranges: from elastic strains ($e<e_y$ where e_y is yield strain) and up to ultimate fracture strains e_f that may exceed e_y by factor of 500) is the key task in solving the problems indicated above. The power-low equation (1) that relates normalized stresses and strains is considered to be the most theoretically and experimentally sound:

$$\overline{\sigma} = \overline{e}^m \tag{1}$$

where m is the strain hardening exponent $0 \le m \le 1$, $\overline{\sigma} = \sigma / \sigma_y$, $\overline{e} = e / \sigma_y$.

The studies (Makhutov, 2018; Makhutov, Matvienko, Romanov, 2018) made it possible to establish the dependencies of the parameters σ_y and m from the strain rates $\dot{e} = de/d\tau$, temperatures t, and the number of loading cycles N in the form $\{\sigma_y, m\} = F(\dot{e}, t, N)$. The functional $F(\dot{e})$ may be described by the power-law expression, functional $F(t)$ is an exponential one. The functional $F(N)$ can be approximated by power-law and exponential forms for cyclically hardened and softened materials respectively. Damages d accumulated in the process of the transition from normal to the abnormal and catastrophic states causes changes in the parameters σ_y, m, and they, in turn, change the dependence $d = f(\overline{\sigma}, \overline{e})$.

The second key task is the analysis of the kinetics of local states of stresses and strains ($\overline{\sigma}_{\max c}$, $\overline{e}_{\max c}$) in notch zones for elastic, limited elastoplastic and severe plastic strains. For this, a modified Neuber equation is used in the form:

$$\{K_\sigma, K_e\} = F\{\alpha_\sigma, \overline{\sigma}_n, m\} \tag{2}$$

where K_σ and K_e are the stress and strain concentration factors in the inelastic region at $(\overline{\sigma}, \overline{e}) > 1$; K_t is theoretical stress concentration factor in the elastic region; $\overline{\sigma}_n$ is the normalized nominal stress.

Using the dependence of m on loading conditions, one can obtain the laws of the redistribution of local stresses and strains that determine the rate of damage accumulation $d = f(t, e, N)$.

The third task consists in a justified selection of the criterion of ultimate damage and fracture. The strain based criterion is the most promising for solving complex practical problems.

$$\overline{e} = \overline{e}_c \text{ and } \overline{e}_{\max c} = F\left\{\overline{e}_c, I_\sigma, D_e\right\} \tag{3}$$

where I_σ is the design factor describing the increase in resistance to deformations, and D_e is the factor that characterize the a decrease in ductility due to stress triaxiality. According to experiments $1 \le I_\sigma \le 2{,}5$ and $0{,}4 \le D_e \le 1$.

The fourth in this set of problems is the problem of nonlinear fracture mechanics for a wide range of strains occurring at the crack tip. An approximate analytical expression for determination of the strain intensity factor was proposed in (Makhutov, 2008) that is based on the theory of concentration of stresses and strains at the crack tip:

$$\overline{K}_{Ie} = F\left\{\overline{K}_I, \overline{\sigma}_n, m\right\} \tag{4}$$

where $\overline{K}_I$ is the normalized stress intensity factor in linear fracture mechanics.

The effects of mechanical static, long-term, cyclic, electromagnetic, corrosive and radiation impacts can be introduced into the above equations.

3. New problems of nonlinear mechanics of deformation and fracture

The solution of the above four main problems for modern extremely loaded facilities allowed analyzing new problems, including those for extreme impacts. These problems include thermo coupled problems of transition from the initial isothermal formulation to the nonisothermal ones with temperature $t_{max\ n}$ increased due to inelastic deformation processes taking into account expressions (1) - (4):

$$t_{\max n} = F\left\{\alpha_t, m, \overline{\sigma}_n, N, \dot{e}, K_{Ie}, K_t\right\} \tag{5}$$

where α_t is an indicator of the initial increase in temperature with increasing strains.

Experiments with high-frequency cyclic loading showed an integral growth of temperature $t_{\max n}$ on 100 ÷ 600°C, and melting of metal at the notch roots and crack tips for specimens with notches and cracks. For highly loaded facilities of the rocket and space technology that work under high initial operating temperatures, high pressure and the presence of aggressive environment, such a high-frequency cyclic loading led to the occurrence of a new limit state with metal ignition.

These problems of deformation, damage accumulation and fracture under extreme loading regimes that should be studied using equations (1) - (5) are considered in details in the next paragraphs.

4. Scenarios of reaching limit states

The list of key problems focused on ensuring safe service life of high risk facilities includes: (1) analysis of the risks of accidents and catastrophes based on limit states, strength and service life criteria; (2) reduction of risk of potential accidents at existing facilities according to the criteria of an extended service life (Makhutov, 2017; Makhutov, Gadenin, Reznikov, et al., 2017). These tasks can be considered either independent or united by general principles and approaches to ensuring safety of the engineering environment.

The system of governing equations for assessment of risks R can be written as:

$$R=F\{U, P\};\ U=F\{U_N, U_T, U_S\};\ P=F\{Q, N, t, \tau, S\} \tag{6}$$

where U is the expected losses, P is the probability of occurrence of a catastrophic situation; U_N, U_T, U_S are losses for the population, technical facilities and the environment respectively, Q are external and internal impacts, N is the number of loading cycles, τ is the duration of exposure to loading, t is the temperature, S are parameters of resistance of materials and structural components to external and internal impacts.

Limit states of a technical facility during its life may be reached at different rates and along various trajectories depending on the conditions, modes and nature of loading. At the same time, at each stage of the facility's life cycle, an assessment of the accumulated damage under various loading conditions is carried out (Fig. 1) and a decision regarding the possibility of its further operation is made, with taking into account the accumulated damage and possibility of extending the facility design life (Makhutov, 2008; Gadenin, 2014; Gadenin, 2018).

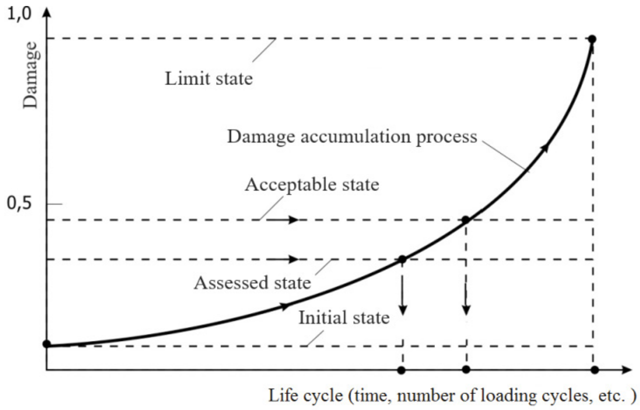

Fig. 1. Parameters of damage at various stages of facility life cycle

A well-developed methodology for the calculation of a set of parameters that determine the degree of damage for the analyzed facility at the stage of its normal operation is usually available (Makhutov, 2008). At the same time, the system of calculations characterizing design basis, beyond design basis and hypothetical situations is based on the analysis and consideration of the conditions for the occurrence of damaged and limit states that lead to emergency and catastrophic situations. In the transition from the analysis of normal operation conditions to the analysis of beyond design basis and hypothetical emergency and catastrophic situations the criteria and regulatory bases for conducting calculations is currently practically missing (Makhutov, 2017; Makhutov, Gadenin, Reznikov, 2017).

Fig. 2 illustrates conditions of operation of engineering facilities. The factors of external impacts on the facility and its reactions on these impacts S^* are depicted on the vertical axis while the horizontal axis shows the level of influence of factors of operating conditions F^e (number loading cycles, time of exposure to load, temperatures, corrosive environments).

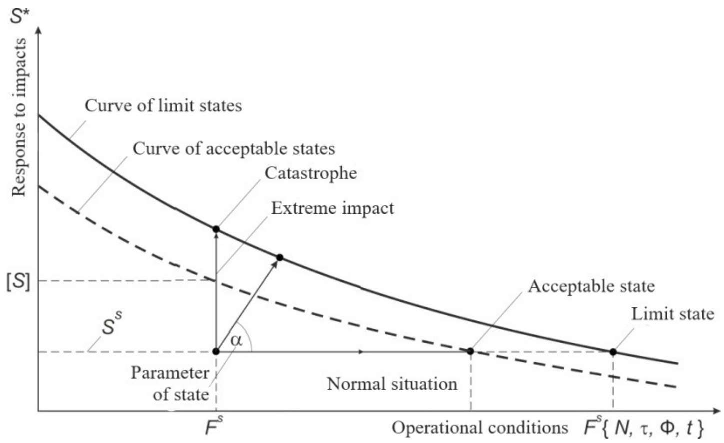

Fig. 2. States, scenarios and factors of operational loading

The area below the dashed line that corresponds to the acceptable states includes normal situations with the operation of the facility within the parameters assigned in accordance with the design standards. The point with the parameters «*S-F*» characterizes the current operational state of the facility.

A critically loaded element of a facility can transit from this point into dangerous (limit) states along various trajectories characterized by an angle α (scenario parameter). For example, moving to the right (at α=0) and staying in the region of normal operation conditions up to the moment of crossing the limit state (solid line), one may estimate the limit service life (expressed in terms of N or τ) or the allowable service life (up to the crossing the dashed line).

Rising from the point of the current state upwards (at $\alpha=90^0$) the facility can reach the ultimate state, followed by a catastrophe, already at this stage of operation. In this case, the task of analyzing safety of the facility in such a scenario should be solved using a methodology that is completely different from the norms applicable in case normal situations. In this case, the current regulatory stress based analysis that uses the existing analytical base is insufficient.

For more accurate strain-based analysis it is necessary to use diagrams of static, cyclic, and long-term deformation of the material with the analysis of states of stresses and strains in the region of severe elastoplastic deformations. This approach is also required in the analysis of forced loading modes ($0\leq\alpha\leq90^0$).

5. Types of operational emergency and catastrophic situations

Emergencies and catastrophic situations can be caused by extreme loads Q, high number of cycles N, long periods of operation τ, low or high operating temperatures t, reduced characteristics of resistance to impacts S. Five types of normal, emergency and catastrophic situations are distinguished in the frame of the theory of safety of technical systems. These include: normal operating conditions, deviations from normal conditions, design basis emergencies, beyond design basis emergencies and hypothetical emergencies (Makhutov, 2017; Makhutov, Gadenin, Reznikov, 2017)

When analyzing risks of beyond design basis emergencies, it is not possible to foresee all sources, causes and scenarios of the occurrence and development of damage. The ability to counter these situations is not sufficient. In these cases, a long shutdown of the operation of the facilities, carrying out complex restoration and rehabilitation work is required. Hypothetical catastrophic situations can occur at facilities with a high level of potential hazards.

From scientific, engineering and technical point of view, the most relevant analysis of the risks of accidents and catastrophes comes down to a comprehensive consideration of severe beyond design-basis and hypothetical situations and determination of the corresponding parameters Q, N, t, τ, S included in the functionals F for P and R according to the expressions (6). In relation to particular facilities, the values of extreme impacts can reach maximum values $Q_{\max}$ causing catastrophic situations. In comparison with the normalized values Q_n under these conditions the load growth factor k_Q can be in the range from 1.5 to 5 or even exceed these values:

$$Q_{\max}=k_Q\, Q_n. \tag{7}$$

The values of k_Q can be determined by calculation and can be set taking into account the actual data on hypothetically possible impacts.

The change in the resistance of materials and structural components to deformation and fracture S turns out to be the most complex one and is described by nonlinear dependences. In the most general case the dependence of this factor on the associated parameters has the form:

$$S=F\{f[\sigma,e],\ N,\ t,\ \tau,\ l\ (\sigma_{\mathrm{u}},\ \sigma_{\mathrm{y}},\ \sigma_{-1},\ \sigma_{\mathrm{c}},\ e_{\mathrm{c}},\ \sigma_{\tau},\ \sigma_{\mathrm{ta}})\} \tag{8}$$

where $f\,[\sigma,e]$ is the stress-strain curve of the material (constitutive equation); l is the size of the crack (defect), σ_{u} is the ultimate strength, σ_{y} is the yield strength, σ_{-1} is the fatigue limit,.σ_{ta} is the tensile strength under axial loading, σ_{c} and e_{c} are critical stresses and strains, σ_{τ} is stress rupture strength.

The functional (8) can be written in various forms: in the form of the constitutive equation, *SN* curves, stress rupture curves, fracture curves (Makhutov, 2008; Gadenin, 2017).

As the methods for design, testing, diagnostics and operation of high-risk facilities are being developed and improved, several basic approaches and criteria are used, including the basic theories and equations of mechanics of deformable solids: strength of materials, elasticity theory, plasticity theory, theory of fatigue, theory of long-term strength, fracture mechanics. The traditional approach consists in sequentially complication of the design criteria. It should be noted that the analysis of strength and service life is carried out in almost all cases, while the application of the criteria for safe operation and risks is much less common in practice. In the general case, the analysis of the service life and risks should include complete sets of emergency and catastrophic situations, as well as the sets of corresponding limit states and criteria.

6. Types of Limit States

The following types of limit states can be considered when the assessment of strength, service life and risks is carried out in accordance with the results of the assessment of real operation conditions and damage to engineering facilities, as well as in accordance with experimental and design investigations of the laws of deformation, damage accumulation and fracture(Makhutov, 2008; Makhutov, 2013; Gadenin, 2013;Makhutov, Gadenin, et al, 2014).

The following limit states should be considered for normal situations, when the regulatory requirements for design, calculation, manufacturing, testing and operation are satisfied:

- fracture under static loading (here the ultimate strength are the design resistance, and the operational loads from internal and external impacts are design loads);

- the development of unacceptable plastic deformations (in this case the yield strength should be considered as the design resistance and the design loads are the same);

- general or local loss of stability (the critical resistance in this case is the critical stress that causes the loss of stability, and the design loads are induced by external and internal impacts that create compressive stresses, for example, axial, hoop and bending stresses for pipelines and vessels);

The following additional limit states can be introduced and considered to conduct the advanced analysis of strength, service life and risks in normal situations:

- The occurrence of cyclic (fatigue) failure in the low- and high cycle fatigue regions. In this case, the combined characteristics of ultimate strength, yield strength, ultimate ductility fatigue limit are used as design resistance, while cyclic loads are considered as design loads;

- The occurrence of brittle fracture. In this case, the design resistance is characterized by fracture toughness or critical values of stress intensity factors, and the design loads are represented by the external and internal loads that cause predominantly tensile stresses;

- The development of cracks (defects) of a mechanical or corrosion-mechanical nature. The design resistance is determined by the cyclic crack resistance, and design loads are determined by cyclic impacts.

For these types of limit states the design resistances are determined according to the norms and standards, and the corresponding typical structural forms (shells, plates, rods) are introduced into the design equations. Nominal stresses and strains under normal conditions, as a rule, remain elastic, and external impacts are usually linearly related to displacements. The aforesaid allows us to simplify the engineering calculations of strength and service life.

Abnormal, and emergency situations, occur when the requirements of standards are not satisfied due to a number of structural, technological or operational factors. Moreover, a deviation from the standard operating parameters enhances the effect of these factors, causing a transition from normal to emergency and catastrophic situations. In such a transition, an analysis of the above mentioned limit states is insufficient, and in some cases not adequate to the scenarios for the development of these situations. In this case new types of limit states that correspond to emergency situations should be introduced into the analysis:

- ductile or brittle fractures with an extreme (by 50-90%) drop in load bearing capacity (in this case, critical fracture stresses for damaged structures should be considered as design resistance and the design loads are caused not only by external and internal impacts, but also by the damage that arose);

- cyclic fracture with an extreme drop (by 1-2 orders of magnitude or more) of durability (here fracture cyclic stresses that depend on the degree of damage are considered as the design resistance, and cyclic loads at different stages of the emergency development are treated as the design loads);

- fracture due to the action of secondary factors of developing emergency situations (here fracture and critical stresses for the above mentioned limit states are design resistance, while initial loads and additional loads, caused by fougasse, thermal and reactive impacts induced by the developing accident are design loads);

- mechanical and thermal damages from the initial and secondary damaging factors without destruction (here the design resistance are critical stresses that have changed due to thermal damage, and the design loads are the combinations of loads in normal and emergency situations).

In the process of accident development that include the above mentioned limit states some catastrophic situations may occur under extreme effects of temperatures exceeding 0.6-0.7 of the material melting point, when the load bearing capacity decrease to extremely low (up to zero) values. In this case the following critical limit states should be cosidered:

- metal melting (local heating due to local impacts with large amplitudes of plastic strains that exceed 0.1-0.5%, and high frequencies that exceed 10-100 Hz);
- metal melting due to the uncontrolled development of nuclear reactions during catastrophes at nuclear power reactors;
- local overheating (by 200-1,000^{0}C) in the zones of high-frequency plastic deformation, followed by ignition in an oxygen atmosphere under high pressure (for example in oxygen-hydrogen liquid-propellant rocket engines);
- overheating with melting from the catastrophic impact of local plasma or laser sources (for example, the impact of special military systems).

The most difficult is the analysis of limit states that include complete phase transitions (solid state $\rightarrow$ melting with a transition to a liquid state $\rightarrow$ evaporation with a transition to a gaseous state $\rightarrow$ the appearance of a plasma state). These states are typical for the action of plasma and electron beams in thermonuclear installations, space particles, kinetic installations.

These limit states were and will remain not only the in the focus of development of regulatory and normative basis, but also in the scope of further scientific research. Additional limit states are becoming more and more relevant for the increasingly complex normal operating conditions of both traditional engineering facilities and for the unique ones. New types of extreme emergency states are becoming the subject of research for unique highly loaded facilities. Their quantitative description and assessment constitutes the scientific essence of the upcoming design and experimental developments focused on ensuring safe service life of these facilities.

For new limit states typical for accident situations, along with the above mentioned parameters of mechanical properties, the laws and equations of nonlinear mechanics of deformation and fracture, as well as the dependences of fracture stresses σ_c and numbers of cycles to failure N_c on the effect of extreme damage factors, should be used. In this case, the influence of the exhaustion of plasticity, the growth of residual tensile stresses, the degradation of the material during operation, with accounting for the scenarios of the development of emergency and catastrophic situations on the characteristics of the design resistance are becoming critically important.

7. Thermomechanical patterns of deformation processes

In most cases, the employed fundamental laws of deformation and fracture are considered for the cases of isothermal loading conditions in a deterministic formulation. Here the room (t=20°C), low (up to-60°C), cryogenic (up to-267°C), elevated (up to 350°C) and high (over 400°C) temperatures are selected as the base ones. Non-isothermal loading conditions in the general case can be caused by an external change in temperature and the environment, as well as an internal temperature change due to the processes heat release in structural materials during their elastoplastic deformation.

The investigation of the factors of the external non-stationarity of the processes of deformation and fracture showed that extreme temperatures and extreme loads have the most influence on strength and service life (Makhutov, 2008). The internally non-stationary and non-isothermal process of material deformation is due to the transition of the mechanical energy of inelastic deformation into heat. In this case, one part of this spent mechanical energy (A) is absorbed by the material (E), and the other is dissipated in the form of heat (Q_e) into the environment and adjacent components (Ivanova, 1975; Troshchenko, 2005; Romanov,1988; Gadenin and Romanov, 1978; Makhutov, Rachuk, Gadenin, 2011). In this case, the equation the energy balance can be written as:

$$A = E + Q_e . \tag{9}$$

The value of the mechanical energy A expended on the deformation of the material is determined be the equation

$$A = \int_{l_0}^{l_k} F d\, l \tag{10}$$

where F is the force, l_0 and l_f are the initial and the final length of the deformable solid. It can be estimated as the area below diagram of the static fracture plotted in the coordinates "force-elongation" (F-Δl) or by the sum of the areas of the cyclic deformation diagrams (hysteresis loops) in each cycle.

The method for precision measuring (with a gradation of up to 0.01°C) the temperature of the self-heating of a deformable specimen was used to determine the fraction of energy that is released in the form of heat during the experiments (Gadenin and Romanov, 1978). Studies of changes in the temperature of a specimen placed in a vacuum chamber and thermally insulated from the loading system (Gadenin, 2018; Gadenin and Romanov, 1978) conducted for various conditions and stages of its deformation made it possible to obtain the corresponding analytical and experimental results.

The results of experiments on specimens made of Cr-Mo-V steel (12X2MFA) under tension in vacuum (Gadenin, 2018) fit well with the linear dependence of a decrease in temperature ΔT in the region of elastic deformation (Geil and Feinberg, 1970; Yastrzhembsky, 1953) with an increase in true stresses $\Delta\sigma_{true}$ (Fig. 3).

$$\Delta T = \frac{T \alpha_T \Delta\sigma_{true}}{\rho C_p} \tag{11}$$

where T is the absolute temperature (K), α_T is the linear temperature expansion coefficient which is equal to α_T=1/3β_T (β_T is volumetric thermal expansion coefficient of the material), ρ is the material density, C_p is the specific heat capacity of the material.

An increase in the temperature of the material is observed upon transition to the region of elastoplastic deformation both in tension and compression. For the static tension the diagram recorded in the stress – temperature coordinates has the form shown in Fig. 4a. In this case the inflection point that is located after the temperature decreasing section corresponds to the elastic limit and is followed by the region of temperature increase that is accompanied by the development of plastic deformation. As the plastic deformation goes up, the temperature, as shown by the experiment, increases according to the dependence that is close to linear (Fig. 4b).

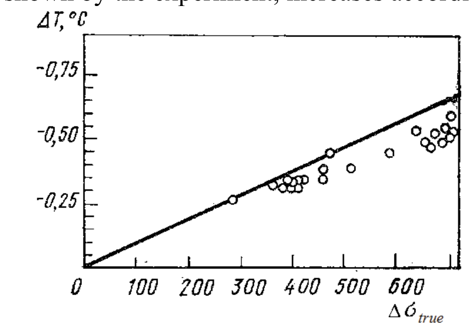

Fig. 3. The theoretical dependences (line) and experimental data (points) on the change in temperature of the specimen material during elastic deformation

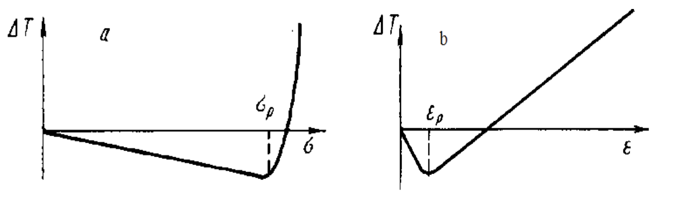

Fig. 4. Diagrams of the change in temperature during elastoplastic deformation against stresses (a) and strains (b)

The results of a series of tests on static elastoplastic deformation of specimens made of 12Kh2MFA and Kh18N10T steels under uniaxial tension (Gadenin, 2018) showed that during uniform deformation, a practically linear increase in temperature was observed with an increase in plastic strains e_p. (fig. 5).

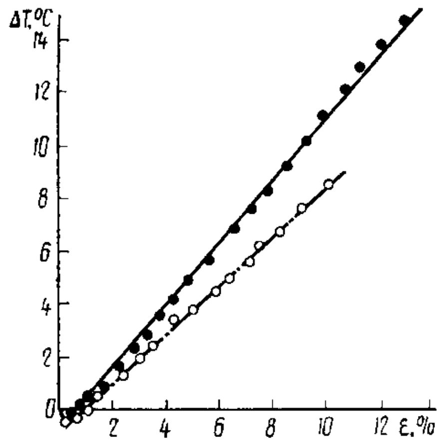

Fig. 5. Temperature of heating of the specimen material against strains for steels 12X2MFA (solid line) and Kh18N10T (dash-dot line)

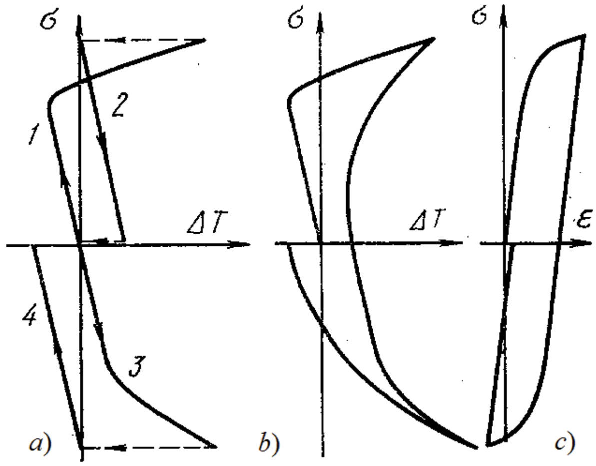

Fig. 6. Dependencies of the change in temperature against stress: (a) during deformation with intermediate stops, (b) during continuous cyclic deformation and (c) the diagram of cyclic deformation in the stress-strain coordinates corresponding to these processes

The stress – strain diagram for cyclic elastoplastic deformation represents a loop of plastic hysteresis (Fig. 6,c). When the diagram of temperature changes against a change in the applied load is recorded some kind of the temperature loop occurs (Fig. 6, b), the regions of this diagram that are related to the decrease and increase in temperature correspond to the loading stages recorded on the deformation curve (Fig. 6, c).

Here (neglecting the heat removal to the insulated grips of the installation) two thermal processes should be considered: a linear with respect to load decrease (in case of tension) or increase (in case of compression) in temperature due to the development of the elastic deformation and an increase in temperature during the appearance and development of plastic deformation (both in tension and compression). The interaction of these two processes determines the change in temperature of the deformable material in the cycle (Fig. 6, b).

It can be seen that the initial elastic deformation is accompanied by a decrease in temperature, and the beginning of plastic deformation is accompanied by its linear increase (with some natural scatter of experimental points). Moreover, if this dependence is presented in the form:

$$\Delta T = k_t \, e_p \, . \tag{12}$$

Then according to fig. 5, and taking into account a slight decrease in temperature due to the continuing increase in elastic deformation for steel 12Kh2MFA the value of the coefficient k_t will be equal to $1.12 \cdot 10^2$ deg·m/m, and for steel X18H10T k_t=$0.82 \cdot 10^2$ deg·m/m.

Due to an increase in temperature under the cyclic loading the changes in the diagrams of cyclic deformation and characteristics of the heat sink, the analysis of temperature non-stationarity is becoming complicated. However, experiments have shown the continuity of the use of expression (12) and the validity of the energy-based fracture criterion developed in (Makhutov, 2008; Gadenin, 2018; Ivanova, 1975; Troshchenko, 2005).

In the general case, the results of measurements of the components of the fracture energy for the material subjected to static tension up to fracture and strain-controlled cyclic loading (when the deformation throughout the specimen is assumed uniform, and when fracture occurs after the nucleation and development of a fatigue crack without the formation of a neck), showed that the specific fracture energy in these two loading regimes is approximately the same. However, the ratio of the work of mechanical forces, determined by the area of the diagrams of static deformation, to the total area of the diagrams of cyclic deformation can decrease by tens and hundreds of times if the number of loading cycles during tests without thermal insulation is increased. This is due to intensive heat sink through the grips and heat dissipation into the environment during cyclic deformation. If there is no such heat sink and heat dissipation and the deformation process is close to the adiabatic one, then, in accordance with the data presented in Fig. 5 and equation (12), local heating of the working part of the specimen can be significant (Makhutov, 2008; Makhutov, 2013).

8. Coupled thermomechanical limit states in the zones of stress concentration and cracks

The above results of the studies of thermomechanical processes of static and cyclic elastoplastic deformation were used to analyze such processes in the zones of stress concentration and cracks (Makhutov, 2008).

The coupled thermomechanical behavior of metals is manifested in the change in their temperature during deformation under conditions of homogeneous and inhomogeneous states of stresses. Here local heating or cooling of metals due to reversible (purely elastic) deformation, as well as heat due to inelastic processes: internal friction, plastic deformation are distinguished.

As noted above, experiments on the study of the release of heat during plastic deformation under conditions that are close to adiabatic ones showed that most of the irreversible work of plastic deformation A_p is converted to heat Q; the ratio Q/A_p lies in the range 0.7–0.95 and depends on loading conditions. In this regard, during further analysis, one can assume that the increase in local temperature under monotonic loading is proportional to the increment of plastic strain in accordance with expression (12).

The heat exchange and heat conductivity equation for coupled elastoplastic deformation can be written as

$$c\dot{T} = \eta\,\sigma_{ij}\,\dot{e}_{ij}^{p} - \alpha\,T\,\delta_{ij}\,\dot{\sigma}_{ij} - q_{i,i} \tag{13}$$

where c is the volumetric heat capacity; T is the absolute temperature in degrees K; σ_{ij} are components of the stress tensor; e_{ij}^{p} the components of the plastic strain tensor; η is the factor characterizing the fraction of energy (power) $\sigma_{ij}\ e_{ij}^{p}$ that is converted into heat; α_T is the coefficient of thermal expansion; δ_{ij} is the Kronecker symbol; $q_{i,j}$ is the divergence of the heat flux vector and dots denote time derivatives.

During the loading cycle, the coupled behavior in the elastic and elastoplastic segments of deformation and the presence of heat sink lead to the formation of a temperature loop. For most loading regimes of structural components and notched specimens heat generation during plastic deformation does not lead to significant heating and loading can be considered isothermal. The growth of nominal loads, frequencies, and the presence of strain concentrators lead to the occurrence of nonisothermal conditions in hazardous areas.

In a number of cases, tests for low-cycle fatigue of smooth specimens are accompanied by relatively small temperature increments (0.5–5°C) per cycle (see Fig. 5) and a slight heating is observed at the moment of fracture (at N=10^2–10^3). However, at the increased frequencies (10^1 - 10^2 cycles/s) and amplitudes of plastic deformation e_{ap}>1%, when the heat sink through the grips and the environment decreases, the temperatures in the working part of the specimen can increase up to 500 - 800°C. In some cases, at large amplitudes of plastic strains melting in the central part of the specimen may occur instead of plastic fracture (Makhutov, 2008; Makhutov, 2013).

When analyzing coupled thermomechanical fields at the crack tip, a high concentration of strains in this region should be taken into account. The heating of the material will be accelerated and accompanied by the formation of a zone of local temperature increase. The coupled fields (level lines) of the intensity of elastoplastic strains (estimated using finite element method for a plane stress state) and temperature (measured by a thermal imaging system) for 15Kh2NMFA steel are shown in Fig. 7a and 7b, respectively.

The deformation softening of the metal at the crack tip contributes to further self-heating. An increase in temperature affects the course of deformation and fracture. This includes the moments when the transition temperatures are reached and a sharp change in the deformation properties of steels occurs. In an in-depth study of this problem, attempts were made (Makhutov, 2008) to simulate and experimentally verify the processes of thermally coupled deformation both for smooth specimens and for the regions of stress concentration at the crack tip. Experiments on thin tubular specimens (20 mm in diameter and 1 mm in wall thickness with a hole of up to 3 mm in diameter or an initial crack with a length of up to 2 mm) subjected to loading frequencies in the range of 70-100 Hz showed that local temperatures may reach 500-1000°C.

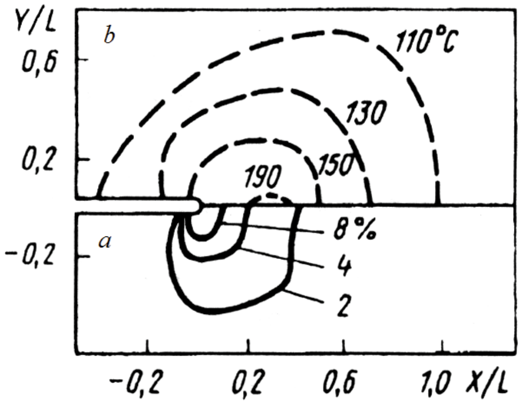

Fig. 7. Coupled fields (level lines) at the tip of the crack of length L under cyclic loading

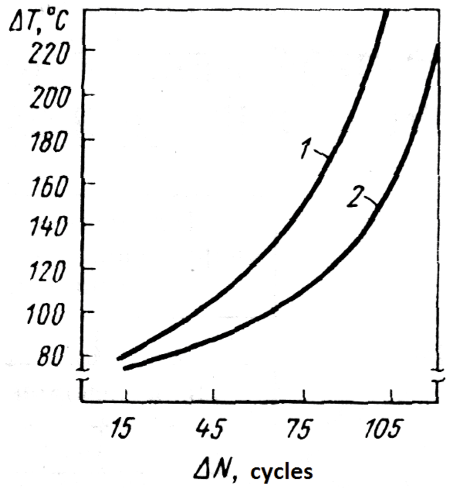

Fig. 9. The increment of the maximum temperature in the specimen, recorded on the basis of cycles ΔN for two loading levels: Level 1 corresponds to 570 MPa and Level 2 corresponds to 510 MPa

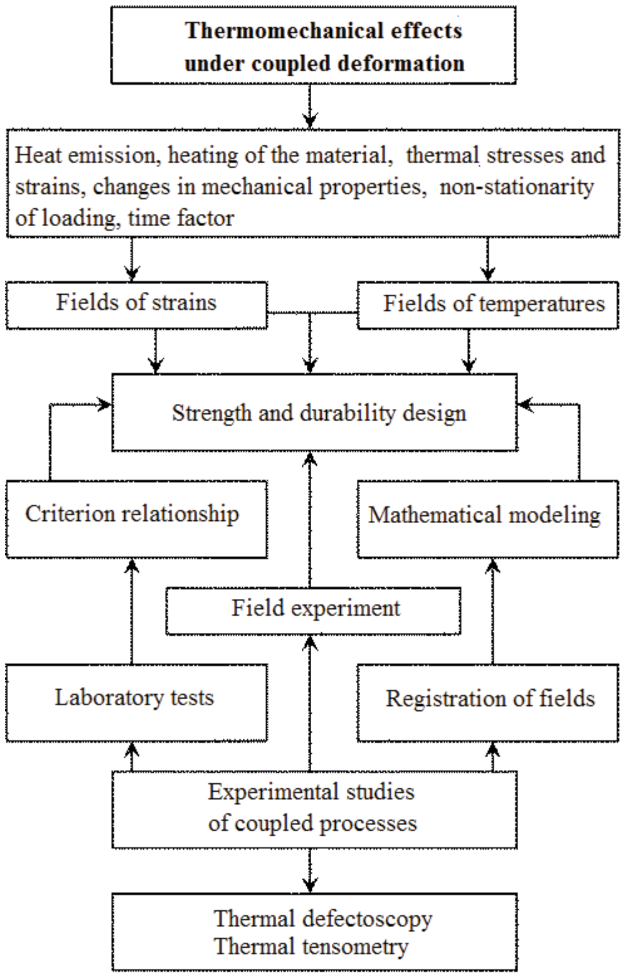

Fig. 8. Flow-chart for a comprehensive study of the process of coupled thermomechanical deformation

The problem of studying coupled elastoplastic deformation is related to the problems of thermocoupled and holographic diagnostics and flaw detection, criterial energy relations and constitutive laws.

The combined use of experimental and numerical methods allows considering the main factors that appear during the implementation of coupled regimes, to evaluate strength and durability of the structure under conditions of non-stationary non-isothermal deformation (Fig. 8).

The finite element method can be applied to get a numerical solution of the problems related to the thermomechanical deformation. The method allows one to obtain algorithms and codes for determining uncoupled mechanical and temperature fields. A complete mathematical formulation of the coupled thermomechanical problem leads to an increase in the number of unknown parameters that should be determined simultaneously, and significantly complicates the implementation of the FEM. In this case mechanical and temperature problems at each time step can be considered separately with the subsequent refinement of the solutions.

A complex experimental installations were used to experimentally study the processes of local plastic deformation, heat generation, heating, and damage accumulation. These include thermal imaging system, holographic stationary and pulsed installations, as well as acoustic emission systems. They made it possible to measure and analyze the strain and temperature fields on the surface of specimens and structural components in the ranges from 0.001 to 0.3 (for strains) and from 20°C to 850°C (for temperatures), by detecting holographic patterns and short-wave infrared thermal radiation.

Figure 9 shows examples of temperature fields caused by plastic deformations. A region of local temperature increase in the center of the flat, 3 mm thick specimen made of Cr-Ni-Ti steel (12X18H10T) is registered on the thermograms of deformation processes that were conducted at a rate of $\dot{e} = 5 \cdot 10^{-3}$ s^{-1}. This region coincides with the point of fracture initiation. The maximum temperature at fracture reached 250°C. When the same specimen with an edge crack fractures, the propagation of fracture was observed, accompanied by the advancement of the zone of local temperature increase at the crack tip.

At a certain stage of the fracture process the shape, size of this region, and maximum temperature (~120°C) remained approximately constant due to the intense heat removal to the lightly loaded part of the specimen.

The study of self-heating during cyclic deformation of thin-walled tubular specimens made of Kh18N10T, 12Kh2MFA steels for the initial strain ranges of 0.8-2.5% and frequencies of 0.5-5 Hz showed that heating up to the point of fracture may reach 50-500°C. In the case of a strain-controlled loading, the resulting regimes were close to stationary ones, when the temperature of the working part of the specimens stabilized and did not change much until the moment of the crack initiation. In all cases, the crack initiation site was characterized by the local temperature increase. The simultaneous recording of an elastic-plastic hysteresis loop and expressions (12) and (13) allow one to relate the processes of heat release and irreversible deformation.

The dependence of temperature on time under cyclic loading can be described by the sum of two functions: the vibrational one that is associated with elastic deformations, and the monotonically increasing one which is related to plastic deformations. Estimates of these functions at the room temperature are in a good agreement with the known theoretical and experimental results. Self-heating was considered under cyclic loading of flat, 6 mm thick specimens made of steel 15Kh2NMFA with an edge crack. The specimen was subjected to stress-controlled loading with the stress amplitudes 510-570 MPa, the loading frequency was equal to 10 Hz. The kinetics of the temperature field in the specimen, caused by both cyclic elastoplastic deformations and crack growth was recorded. The values of the temperature increase in the vicinity of crack prior to fracture that were estimated theoretically and obtained experimentally were in the range 200–250°C (Fig. 9).

The results of studies of thermally coupled deformation indicate that heating caused by elastoplastic deformations can be significant and can change the type of limit state. The study of this phenomenon for extremely loaded structures is of particular interest both from the theoretical and the practical points of view. The possibility of occurrence of coupled thermomechanical regimes should be taken into account when design and experimental methods for assessing the strength, service life, survivability and safety of high-risk facilities are developed.

9. Conclusions

The presented above results of studies of the problems of deformation, damage accumulation and fracture under extreme conditions are relevant primarily for highly loaded structures in a number of industries, including: (a) nuclear power engineering with reactors on thermal and fast neutrons (for which a number of conditions for the possible achievement of limit states were associated with ultrahigh durability $N \rightarrow 10^{10}$, with defects l→1000 mm, with explosive technologies and neutron fluxes up to 10^{22} n/cm^2.); (b) thermonuclear engineering facilities loaded by non-isothermal superhigh-speed (up to 270 km/s) electron flows that led to deeper phase transformations (when a solid deformable body of a compressible thin-walled shell with deuterium transit into liquid, gaseous or plasma states; (c) aircraft engineering facilities, that can be subjected to extreme thermal loads at supersonic flight speed; (d) rocket and space engineering facilities (ground-based launch complexes, engine units of launch vehicles), the analysis of the strength and service life of which should be carried out in a coupled thermomechanical formulation. At the same time, when the assessment of strength of thin-walled structures that are struck by plasma flows in local zones is carried out it is important to study the kinetics of thermal fields, temperature stresses, and a drop in resistance to deformation by 20-50%. For thermonuclear installations with magnetic plasma confinement, the analysis of the loss of the state of superconductivity in coils caused by local strains that exceed 0.01–0.02 and friction of the superconducting windings on the casing was of considerable importance.

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