# NONLINEAR DEFORMATION AND FRACTURE MECHANICS FOR ENGINEERING APPROACHES IN DESIGN OF STRUCTURES

**N.A.Makhutov** and **M.M.Gadenin**
*Department of Strength and Engineering Safety of Materials and Constructions, Mechanical Engineering Research Institute, Russian Academy of Sciences, Moscow, Russia*

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**Contents**



**Summary**

The equations for elasto-plastic static and cyclic deformation, force and deformation criteria of quasi-static and fatigue failures, criterion of initiation and propagation of cracks, features of the equations for a linear and nonlinear fracture mechanics are described. The mechanics of nonlinear deformation and fracture is used for calculations of strength, life-time and crack resistance of structures.

## 1. General Load Conditions for Engineering Structures

Advances in science and technology, implementation of large-scale projects and efforts for preservation of ecologically sound environment are associated with the possibility of origination of technogenic, natural and natural-technogenic catastrophes with regional, national and global consequences.

Further development of complex technical systems within the lifetime ranges from seconds (rocket-space vehicles) to 50-100 years (nuclear reactors, engineering facilities) regardless of new safety criteria which characterize these systems' transfer to final condition threatening people and environment, should be considered as unacceptable. Quantitative substantiation for conditions of emergency origination should be calculated not only for normal operation conditions, but also for extremal ones which are caused by fractures, explosions, fires, leakages of radioactive and toxic substances, earthquakes, hurricanes, tsunami, aircraft and space vehicles' crashes, or subversive actions. Safety assurance problem will be of vital importance in the nearest decades in Russia due to expiration of lifetime of large number of power units (including atomic ones), chemical and transportation apparatuses, complete replacement or modernization of which requires significant financial and intellectual expenditures.

The following classification of these objects can be proposed to the reader's attention, taking into account their design structural peculiarities, the level of potential hazard to people and environment in the event of technogenic and natural catastrophes:

- nuclear power engineering sites;
- chemical plants;
- special equipment - rockets, space vehicles, computer-aided systems;
- unique engineering structures;
- civil engineering sites;
- traditional and non-traditional power engineering sites;
- objects of machine building and metallurgy industries;
- transport systems;
- main pipelines;
- equipment for operation in low temperature conditions (Arctic equipment).

Owing to relative stability of general mechanisms of emergency propagation at various types of facilities, it would be advisable to foresee two levels of life and safety norms and standards, while forming general codes structure.

For mentioned above structures with general service time from $10^1$-$10^2$ s to $10^8$-$10^9$ s it is possible to allocate the following areas of loading cycles number:

$10^0$-$10^1$ - extreme cycles (start-up, test, breakdowns);
$10^2$-$10^3$ - operational cycles (starts-up, regulation of capacity, operation of protection systems);
$10^4$-$10^5$ - operational cycles (technological cycles, regulation);
$10^6$-$10^8$ - operational cycles (technological, transport cycles, changes of pressure);
$10^9$-$10^{12}$ - operational cycles (vibration, changes of temperatures and pressure).

The fatigue of metal constructional materials at numbers of cycles in the range $10^0$-$10^{12}$ that are used in complex technical objects, has four characteristic features:

$10^0$-$10^3$ - low cycle quasistatic or fatigue fracture at availability of large microplastic deformations in a zone of failure (when amplitude of stresses $\sigma_a >> \sigma_Y$, where - $\sigma_Y$ is a yield limit);
$10^3$-$10^5$ - *low cycle fatigue* fracture at availability rather small macroplastic deformations in a zone of failure (when $\sigma_e \le \sigma_a \le \sigma_Y$, $\sigma_e$ - a limit of elasticity);

$10^5$-$10^8$ - classical many cycle fatigue fracture at availability of microplastic deformations in micro and macro volumes near a zone of failure (when $\sigma_a \leq \sigma_e$);
$10^9$-$10^{12}$ - fatigue fracture on superhigh bases (numbers of cycles) at availability of microplastic deformations in microvolumes near a zone of failure ($\sigma_a << \sigma_e$).

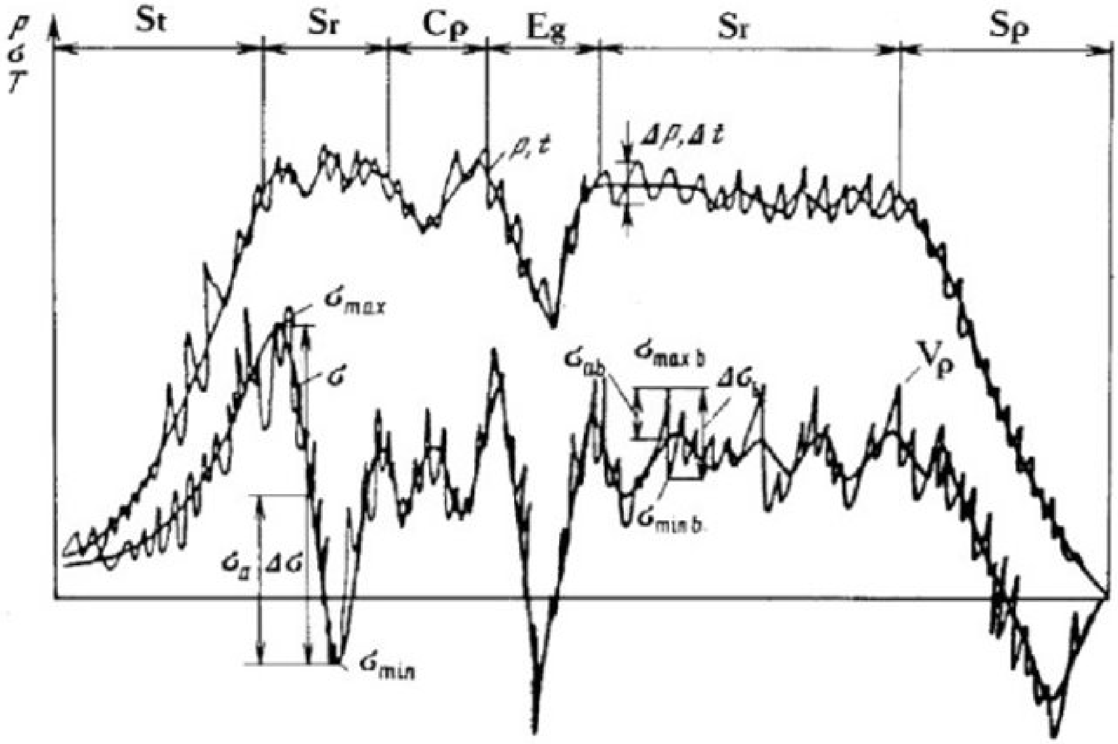


Figure 1. The diagram for change of service loading parameters

Figure 1 shows a scheme of change at time $\tau$ of service loading parameters for a body PVR-reactor. Such parameters are maximal amplitude values:

- pressure of the heat-carrier $p$ ($p_{\max}$, $p_a$, $\Delta p$);
- temperature $t$ ($t_{\max}$, $t_{\min}$, $t_a$, $\Delta t$);
- nominal and local stresses $\sigma$ ($\sigma_{\max}$, $\sigma_{\min}$, $\sigma_a$,) or strain $e$ ($e_{\max}$, $e_{\min}$, $e_a$).

Main service modes are:

- starts-up (St) and hudrotests (Hd);
- stationary modes (Sr);
- change of capacity (Cp);
- emergency modes (Eg);
- stops-up (Sp).

The occurrence of changes of pressure $\Delta p$, changes of temperatures $\Delta t$ and vibrations ($v_p$) gives high-frequency stresses amplitudes $\sigma_{ah}$. It creates two- or frequencies loading with the frequencies relations $f_a/f_{ah}$=$10^1$-$10^5$ and asymmetry factor $r_\sigma = \sigma_{\min}/\sigma_{\max}>0$.

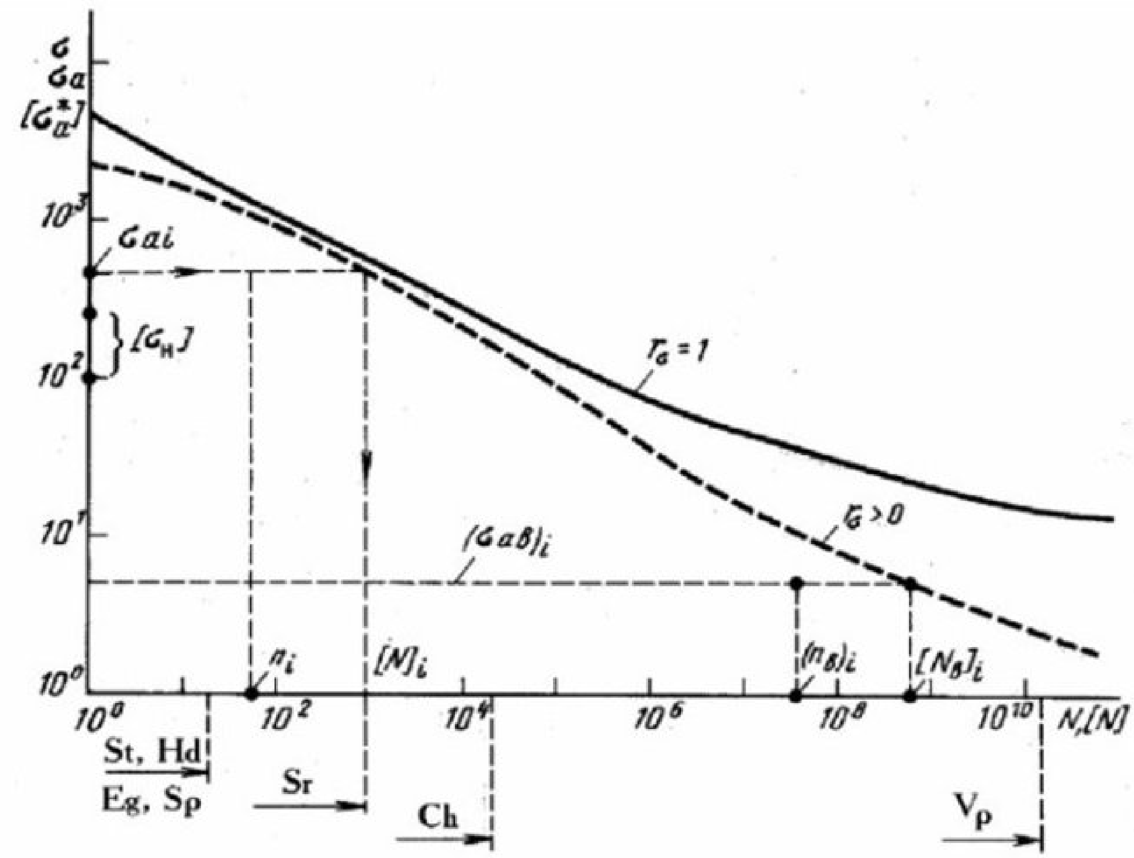


Figure 2. The diagram for determination of the strength and resource characteristics

Engineering diagram for generalized fatigue curve for coordinates "$\sigma$, $\sigma_a$-$N$" is shown on Figure 2. On this figure:

$\sigma_{ai}$, $(\sigma_{ah})_i$ - a amplitude of main and vibrating stresses for *i*-th mode;
$n_i$, $(n_h)_i$ - a number of cycles for main and vibrating loadings;
$[\sigma_a^*]$, $[N]$ - design stresses amplitude and lifetime (number of cycles);
$[\sigma_n]$ - design nominal stresses.

It is possible to determine these stresses from a traditional account of static strength on ultimate $\sigma_u$ and yield $\sigma_Y$ limits.

## 2. Deformation Fracture Criteria under Static and Low Cyclic High Temperatures Loading

The low-cycle loading of structural elements at high temperatures will usually cause an elasto-plastic deformation in the zones of stress concentration. The elasto-plastic deformation redistribution in the concentration zones for the zero (initial) and subsequent half-cycles of loading at given nominal stress amplitudes is facilitated as a result of resistance changes to elasto-plastic deformations under high temperature conditions. The number of cycles to fracture at room and high temperatures depends on the level of deformation redistribution in the zones of stress concentration, and on the fracture deformation criteria. This internal nonstationary character of the process of plastic deformation in the concentration zones at stationary external loadings leads to a deviation of the number of cycles to fracture at a given value of initial deformations or stresses in the concentration zones from that in the case of a stationary loading of smooth specimens at a given stress or strain of the same magnitude.

The stress-strain elasto-plastic relations under cyclic loading determined on smooth specimens are used for the evaluation of the strain redistribution in concentration zones. The analysis of this redistribution reveals that the amplitude will increase in the case of plastic deformations in the concentration zones of cyclic softening materials, and decrease if materials of cyclic reinforcement are tested. The influence of the increasing test temperature as shown in Figure 3 depends on the type of material, test temperature, and strain rate. Decrease of the cyclic plastic deformation with the temperature growth is typical for low carbon ageing steels, whereas an increase is characteristic of low alloyed cyclic softening steels. The influence of strain rate on the amplitude of plastic deformation is connected to the rheological properties of the metal at the corresponding temperature. Extensive experimental investigations on the resistance to low cycle fracture at high temperatures showed that, when the creep effect is negligible, the fracture cycle number at strain-controlled loading is a power function of the plastic deformation amplitude. At temperatures where a creep effect exists, the fracture number of cycles depends on the elasto-plastic deformation amplitude. In this case a combined cyclic and creep damage effect is observed. Experimental data show the dependence of endurance in the stress concentration zone, on the mechanical properties of the material, obtained by testing smooth specimens with a uniform state of stress at normal and high temperatures.

Experimental and analytical results for low cycle failures in the stress concentration zones, in connection with the deformation condition, were analyzed for three types of steel:

*I*. - low carbon, low alloyed steel 0.28% C;
*II*. - low alloyed stainless Cr–Mo–V steel;
*III*. - stainless austenitic steel, Type 18-8.

The test temperature for steel *I* was 20–350°C, for steel *II* - 20-450°C, and for steel *III* - 20–550°C. The creep deformation and damage, under the above temperatures and test frequencies of 1–2 cycles in minute, corresponding to the total test time of 10–40 hours, were not considerable.

Mechanical properties of the steels tested are: elastic limit $\sigma_e$, yield point $\sigma_Y=\sigma_{0.2}$, ultimate strength $\sigma_u$ , cross-section reduction $\psi_k$, hardening index $m_0$.

The influence of test temperature on the basic properties in a static tensile test, expressed in relative values, is shown in Figure 3. The yield point $\sigma_{0.2}$ of all the three types of steel will decrease with an increase of temperature. The ultimate strength $\sigma_u$ of steel *II* and *III* will decrease with arising temperature, whereas the ultimate strength $\sigma_u$

of steel *I* in the temperature range of strain ageing 150–300°C will increase. The plasticity of non-ageing steel *II* will rise and that of steel *III* decrease with temperature. A decrease of plasticity in the temperature range of strain ageing of steel *I* is observed. At a deformation rate of 1.6–3·$10^{-3}$ 1/sec the time of static loading till failure of the steels tested was equal to 2–4 min. Increase of the loading time to failure up to 20 hours at temperatures 350°C for steel *I*, at 450°C for steel *II*, and at 500°C for steel *III* hardly influence the change of plasticity.

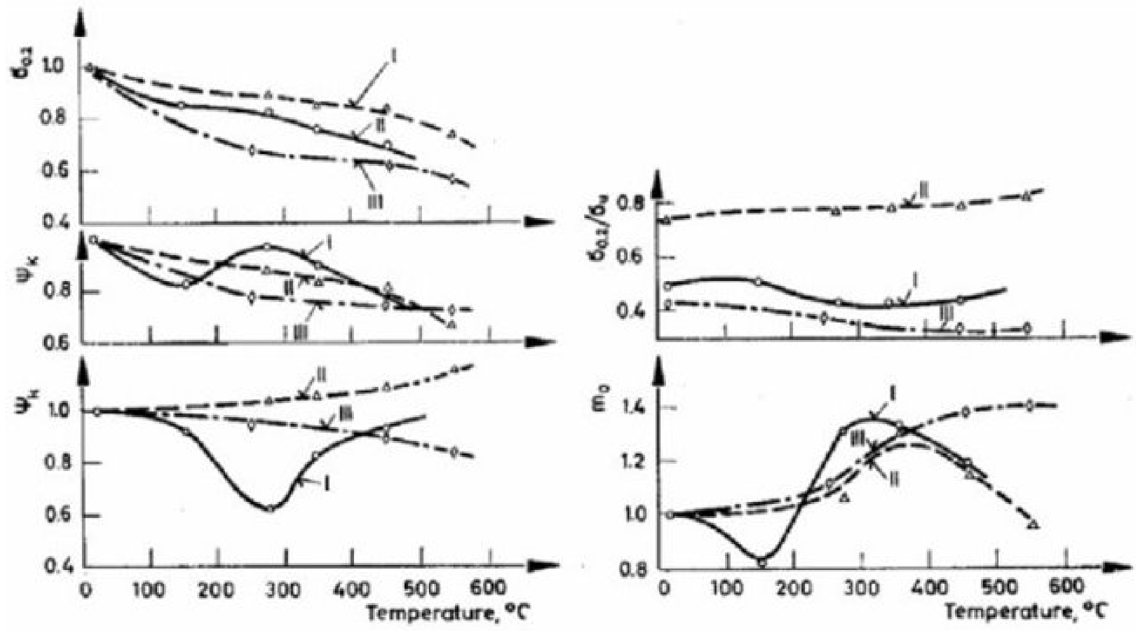


Figure 3. Temperature dependence of mechanical properties

Under low-cycle loading conditions at a uniform stress state the resistance to plastic deformation is described by the stress-strain diagrams under loading, with a given stress or strain rate (Figure 4). These diagrams are plotted as stress values $\overline{\sigma}$; related to the elasticity limit $\overline{\sigma}=\dfrac{\sigma}{\sigma_e}$ and deformation values $\overline{e}$ related**,** in turn, to the deformation at the elasticity limit $\overline{e}=\dfrac{e}{e_e}$. An alteration of the loop width $\overline{\delta}^{(k)}$ and an accumulation of the one-side plastic deformation $\overline{e}^{(k)}$ are observed under stress-controlled loading, as a result of the difference $\overline{\Delta}^{(k)}$ of the loop with between even and uneven half-cycles. An alteration of the maximum stress of the cycle under strain-controlled loading will also take place.

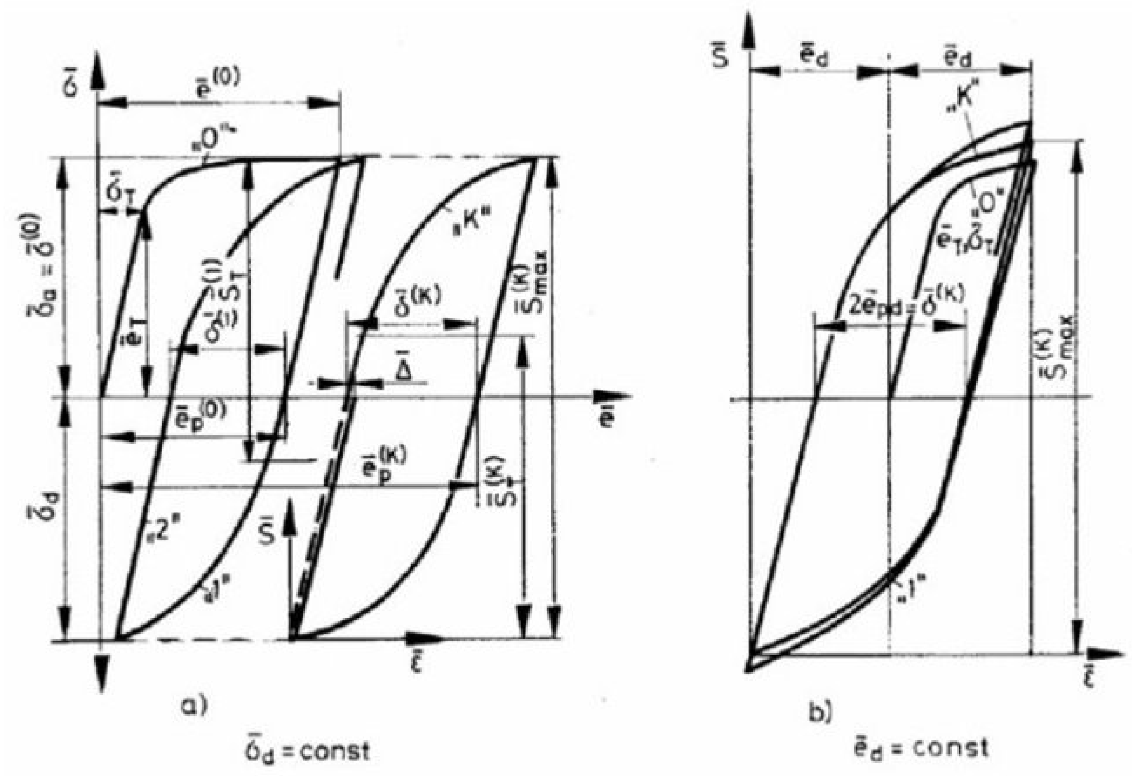


Figure 4. Stress-strain cyclic diagrams

The loop width $\bar{\delta}^{(k)}$ at loading with a given stress amplitude, according the results obtained above can be expressed by

$$\bar{\delta}^{(k)} = A\left(\bar{e}^{(0)} - 1\right)F(k), \qquad (1)$$

where *A* is an experimental defined material characteristic,
$\bar{e}^{(0)}$ is the elasto-plastic deformation in the initial zero half-cycle,
*F*(*k*) is a function of half-cycle number *k* determined experimentally at $\bar{\sigma}^{(a)} = \text{const}.$.

For *cyclic softening* materials $F(k) = \exp C\left(\bar{e}^{(0)} - 1\right)(k-1)$; for *cyclic hardening* materials $F(k) = K^{-B\left(\bar{\sigma}^{(0)} - 1\right)}$. *C, B* are material characteristics (*C*≥0, *B*≥0). For cyclic stable material *B*=0 and *F*(*k*)=1.

Stresses $\bar{\sigma}^{(0)}$ at a power type approximation of the stress-strain diagram of zero half-cycle in the elasto-plastic range ($\bar{\sigma}^{(0)}$≥1) are expressed as depending on the initial deformation $\bar{e}^{(0)}$ by the relation

$$\bar{\sigma}^{(0)} = \bar{e}^{(0)m_0}, \tag{2}$$

where $m_0$ is a characteristic of a power type *hardening* of the material ($0 \le m_0 \le 1$). Their dependence on temperature is illustrated in Figure 3.

According to Eqs. (1) – (2), the loop width in the *k*-th half-cycle for a given material is determined by deformation $\bar{e}^{(0)}$ and the values *A* and *C* (or *B*). The values *A* and *C* are indirectly dependent on the testing temperature. Generalization of the experimental results at normal and high temperatures ($t$=20–550°C) for steels with an ultimate stress from 430 to 1300 MPa has shown that the values *A* and *C* increase with increasing the ratio of yield point to the ultimate stress $\sigma_{0.2}/\sigma_u$. It may be supposed that the dependence of *A* and *C* on the ratio $\sigma_{0.2}/\sigma_u$ is not influenced by the test temperature, but the ratio $\sigma_{0.2}/\sigma_u$ is depending on this temperature according to Figure 3. The experimental data can be approximately expressed by

$$A = 0.16\left(1 + \frac{1}{1-\sigma_{0.2}/\sigma_u}\right),\; C = 1.5\cdot 10^{-3}\left(\frac{1}{1-\sigma_{0.2}/\sigma_u} - 2\right).$$

Steels with $\sigma_{0.2}/\sigma_u > 0.5$ are cyclic softening ($C>0$), and those with $\sigma_{0.2}/\sigma_u < 0.5$ – are cyclic hardening ($C<0$) types.

For cyclic hardening steels ($0.15 < m_0 \le 0.3$) at deformations $\bar{e}^{(0)} < 10$ as shown by the experimental data, between *C* and *B* a nearly linear relation will exist: $C = -3\cdot 10^{-3}B$.

Low carbon steel *I* cyclic stable at $t$=20°C can be cyclic hardening at temperatures up to 350°C. At higher temperatures up to 450°C, the cyclic hardening of this steel will change to cyclic softening. Intensity of the cyclic softening of steel *II* will increase with a rising temperature. The tendency to cyclic hardening of steel *II* with an increasing temperature is increased.

The value of $\bar{\Delta}^{(k)}$ which defines the one-side accumulation of plastic deformation taking into account (1) is equal to $\bar{\Delta}^{(k)} = (A - A_*)\left(\bar{e}^{(0)} - 1\right)F(k)$, where the value $(A–A_*)$ reflects the cyclic anisotropy of the steel. This value can be approximately defined as $(A - A_*) = 2\cdot 10^{-2}\left(\frac{1}{1-0.7A} - 1.3\right)$.

Equation of the stress-strain curve of the cyclic deformation depends on the number of half-cycles $k$ in the co-ordinate system $S$–$\varepsilon$, the zero point of the co-ordinates coincide with the beginning of the load release (Figure 4), and can be written as $\bar{\varepsilon}^{(k)} = \bar{S}^{(k)} + \bar{\delta}^{(k)}$, where $\bar{\varepsilon}^{(k)}$, $\bar{S}^{(k)}$ are the current values of the elasto-plastic deformations and stresses; $\overline{\delta}^{(k)}$ is the loop width according to Eq. (1) at a stress amplitude of $\overline{\sigma}_a = \frac{1}{2}\overline{S}^{(k)}$.

The cyclic stress-strain curve can be written in the analogue form (2):

$$\overline{S}^{(k)} = \overline{\varepsilon}^{(k)m(k)}, \tag{3}$$

where $m(k)$ is a characteristic of the hardening of the current half-cycles. The stress and strain in the co-ordinate system $\overline{\sigma}^{(k)} - \overline{e}^{(k)}$ are equal to $\overline{\sigma}^{(k)} = \frac{\overline{S}^{(k)}}{2}$, $\overline{e}^{(k)} = \frac{\overline{\varepsilon}^{(k)}}{2}$.

Taking into account (1) - (3), we get

$$m(k) = \frac{\log \overline{e}^{(0)\ 1/m_0}}{\log\left[\overline{e}^{(0)\ 1/m_0} + \frac{A}{2}\left(\overline{e}^{(0)} - 1\right)F(k)\right]}. \tag{4}$$

For the cyclic hardening metals, the value of $F(k)$ will decrease and the values $m(k)$ increase with an increased number of cycles. At cyclic softening the inverse takes place. For a cyclic stable steel the value $m(k)$ does not depend on the number of half-cycles.

Under loading with a given amplitude of elasto-plastic deformation $\overline{e}_a = \frac{\overline{\varepsilon}^{(k)}}{2} = \text{const.}$ (Figure 4) the maximum stress values $\overline{S}^{(k)}_{\max}$ change according to Eq. (4) as the loop width $\overline{\delta}^{(k)}$ for cyclic hardening steels and the stress $\overline{S}^{(k)}_{\max}$ rise; for cyclic softening steels the value $\overline{S}^{(k)}_{\max}$ decreases.

The fracture resistance under loading at controlled deformation amplitudes $\overline{e}_a$ =const. for a large group of metals can be described by the well-known Manson–Coffin equation:

$$2\overline{e}_{ap} \cdot N_{ef}^{m} = \overline{C}, \tag{5}$$

where $\overline{e}_{ap}$ – is the amplitude of plastic deformation; $N_{ef}$ – cycle number to fracture; $m$, $\overline{C}$ – steel characteristics.

The index *ef* of the cycle number $N$ indicates fatigue fracture under loading, with a constant strain amplitude $\overline{e}_a$. The index $m$ for low carbon, low alloyed and stainless austenitic steels with an ultimate stress up to 700 MPa is equal to 0,5. Value $\overline{C}$ is defined by the contraction of the neck at a static fracture. $\overline{C} = \frac{1}{2e_T} \ln \frac{100}{100-\psi_k} = \frac{1}{2}\,\overline{e}_k$, where $\overline{e}_k$ is the relative logarithmic deformation of the neck.

In Figure 5 a comparison of the calculation results (smooth line) with experimental data (points) for steels *I* and *II* at temperatures in the range from 20 to 450°C, and the total time to fracture up to 40 hours is shown.

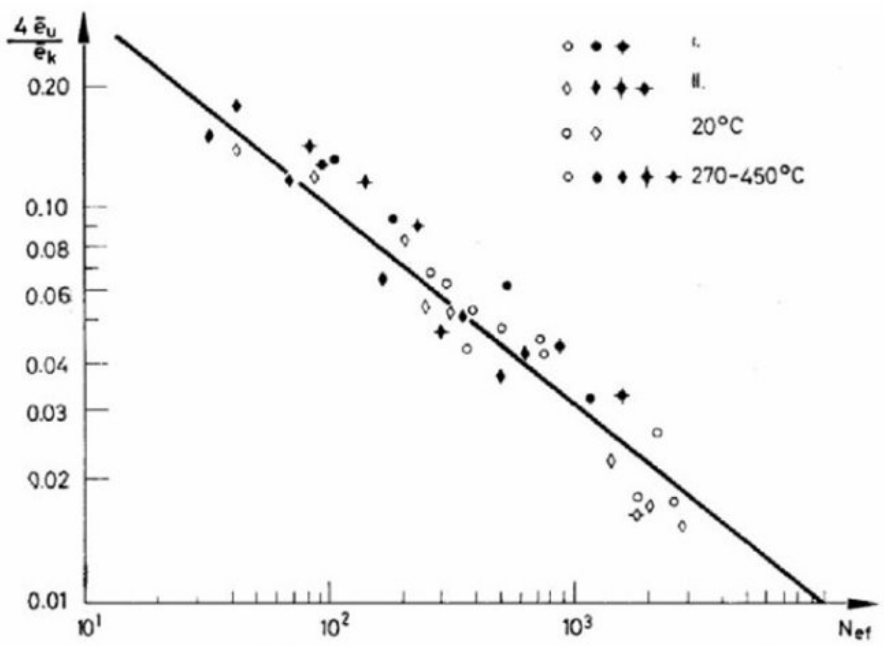


Figure 5. Low cycle fatigue curve expressed in relative values of deformation amplitudes

The condition of fatigue failure can be expressed by using an experimentally confirmed linear fatigue damage cumulative rule, in terms of relative fatigue life $d_f = N/N_{ef}$ and $2\overline{e}_{ap} = \overline{\delta}^{(k)}$ on the basis of the power type equation of the fatigue curve for constant strain loading ($\overline{e}_a$ =*const*.), in the form (5), with index *m* independent of temperature, by the following formula $\int_1^{k_{ef}} \left(\overline{\delta}^{(k)}\right)^{1/m} dk = 2\left(\overline{C}\right)^{1/m}$, where $k_{ef}$ – is the critical half-cycle number to fracture.

Last equation is used for the determination of the critical cycle number $N_{ef}$ at loading with given stress amplitudes $\overline{\sigma}_a$ =*const*., when failure is preceded by the formation of fatigue microcracks. Index $\sigma f$ indicates a fatigue failure under loading, with a constant stress amplitude $\overline{\sigma}_a$. Integration of this equation gives for a cyclic softening steel:

$$N_{\sigma f} = \frac{1.15}{C\left(\bar{e}^{(0)} - 1\right)}$$

$$\lg\left\{\frac{2\bar{C}}{m}\left[\frac{\bar{\bar{C}}}{A\left(\bar{e}^{(0)} - 1\right)^{1-m}}\right]^{1/m} + 1\right\} + 0.5,$$

for a cyclic hardening steel:

$$N_{\sigma f} = 0.5\left\{2\left[1 - \frac{b}{m}\left(\bar{e}^{(0)\ m_0} - 1\right)\right]\right.$$

$$\left.\left[\frac{\bar{\bar{C}}}{A\left(e^{(0)} - 1\right)}\right]^{1/m}\right\}^{m\left[m - B\left(\bar{e}^{(0)\ m_0} - 1\right)\right]},$$

and for a cyclic stable steel: $N_{\sigma f} = \left[\dfrac{\bar{\bar{C}}}{A\left(\bar{e}^{(0)} - 1\right)}\right]^{1/m}$.

Value $\bar{\bar{C}}$ is defined by taking into account the decrease of plasticity as the result of a displacement of the loop in the zero half-cycle at loading with a given stress amplitude. This displacement is equal to the sum of elastic deformation at relief and half of the loop within the first half-cycle

$$\bar{\bar{C}} = \bar{C} - \left[\bar{e}^{(0)\ m_0} + \frac{A}{2}\left(\bar{e}^{(0)} - 1\right)\right].$$

As it was mentioned above, the values *A*, *B*, *C*, $m_0$ are dependent on the test temperature. The value $\bar{\sigma}_a$ is connected with the deformation $\bar{e}^{(0)}$ in the zero half-cycle according to relation (2).

For cyclic anisotropic, cyclic stable, and softening steels under load with a constant stress amplitude $\bar{\sigma}_a$ =*const*., the value of the one-side accumulated plastic deformation during $k$ half cycles is determined by integrating over $k$ the function $\overline{\Delta}^{(k)}$: $\overline{e}_p^{(k)} = \int_1^k \overline{\Delta}^{(k)} dk$.

In the field of a low number of cycles (below $10^3$), the one-side accumulation of plastic deformations leads to a quasi-static failure with neck formation. A criterion for such type of failure is the value of one-side accumulated plastic deformation equal to deformation $\overline{e}_k$ in the neck at static tension rupture. A quasi-static failure of the steels mentioned above in the field of low fatigue life $N_{\sigma s}$ will precede fatigue failure. Index $\sigma s$ at the cycle number $N$ indicates a quasi-static failure under load with constant stress amplitude.

The cycle number needed for quasistatic failure $N$ at loading with a given stress amplitude is determined from the condition that the plastic deformation $\overline{e}_k$ is equal to the sum of plastic deformations in the zero half-cycle $\overline{e}_p^{(0)}$, cyclic accumulated during $k$ half-cycles, plastic deformation $\overline{e}_p^{(k-1)}$, and the plastic deformation of the last half-cycle

$$\overline{e}_p^{(0)} + \overline{e}_p^{(k_{\sigma s}-1)} + \overline{\Delta}^{(k_{\sigma s})} = \overline{e}_k .$$

Deformations $\overline{e}_p^{(0)}$ and $\overline{\Delta}^{(k_{\sigma s})}$ are determined by the curve of static deformation. Deformation $\overline{e}_p^{(0)}$ is equal to ($\overline{e}^{(0)}$-1). Denoting with $\overline{e}_{pk}$ the value of the deformation, we get $\overline{e}_k - \overline{\Delta}^{(k_{\sigma s})} + 1 = \overline{e}_{pk}$.

The cycle number $N_{\sigma s}$, can be determined for a cyclic softening steel

$$N_{\sigma s} = \frac{1.15}{C\left(\overline{e}^{(0)} - 1\right)}$$

$$\log\left[\frac{C}{\left(A - A_*\right)}\left(\overline{e}_{pk} - \overline{e}_{(0)} + 1\right)\right] + 0.5,$$

for a cyclic stable steel $N_{\sigma s} = 0.5\frac{\overline{e}_{pk} - \overline{e}^{(0)}}{\left(A - A_*\right)\left(\overline{e}^{(0)} - 1\right)} + 0.5$, and for cyclic hardening steels (at $B$<0.12)

$$N_{\sigma s} = 0.5\left\{ \frac{\left(\overline{e}_{pk} - \overline{e}^{(0)}\right)}{\left(A - A_{*}\right)\left(\overline{e}^{(0)} - 1\right)} \right.$$

$$\left.\left[1 - B\left(\overline{e}^{(0)\,m_0} - 1\right)\right]\right\}^{1\Big/\left[1 - B\left(\overline{e}^{(0)\,m_0} - 1\right)\right]}.$$

Dependence of the critical cycle number $N_{\sigma s}$ on temperature can be determined by the corresponding temperature dependence $A$, $C$, $B$, $(A–A*)$, $m_0$, $\overline{e}^{(k)}$. Stress amplitude $\overline{\sigma}_a = \overline{\sigma}^{(0)}$ is determined by the deformation $\overline{e}^{(0)}$ in the zero half-cycle of Eq. (2).

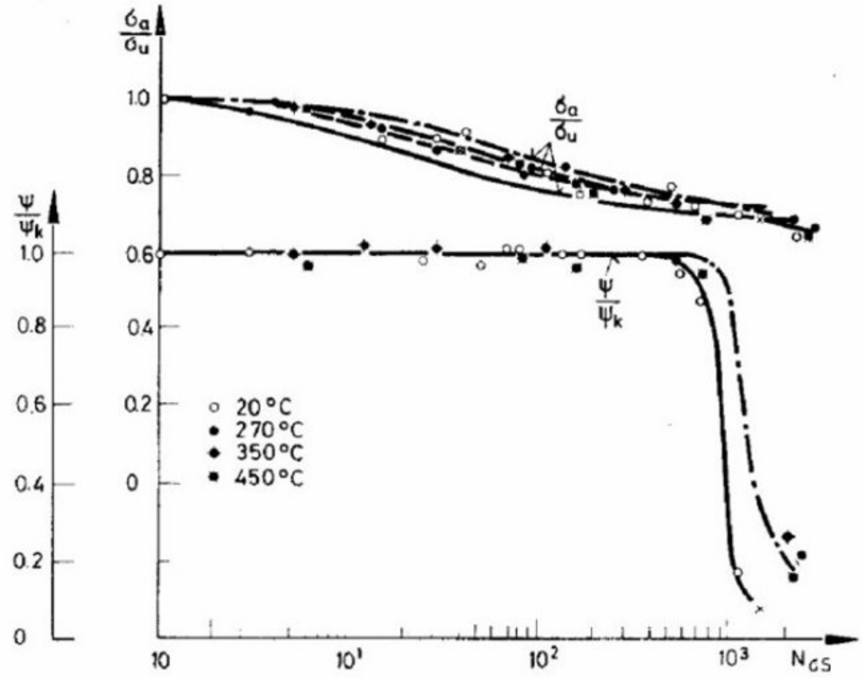


Figure 6. Low cycle fatigue curves in relative values of stress amplitude, and the curves of the relative contraction coefficient values at cyclic rupture

Comparison of the data calculated by (smooth line) with the experimental data (points) for steels *II* and *I* in the temperature range from 20 to 450°C is given in Figure 6. A quasistatic failure of steel *II*, characterized by the value $\psi = \psi_k$ at the temperatures mentioned takes place in the range of the total number of cycles from 1 to $8 \cdot 10^2 – 10^3$. At cycle numbers above $1.5 \cdot 10^3$ the failure under load with a given stress amplitude leads to a fatigue type failure.

With cyclic stable steels *I* at $t$=20–150°C, a quasistatic failure takes place at cycle numbers $5 \cdot 10^1$-$10^2$. The range of cycle numbers at which a quasi-static failure takes place in the case of this steel may decrease to 10. At a temperature of deformation ageing the cycle numbers at which a quasistatic failure will change into fatigue failure are denoted by crosses in Figure 6. Fatigue failure takes place after the decrease of plastic deformation by 60 – 90%.

As for the cycle number at which transition from quasistatic to fatigue failure occurs, this (Figure 6) is defined from the condition that the sum of accumulated quasistatic and fatigue damages is equal to a critical value, as shown by the comparison of the calculated and experimental data. This value is the sum of the ratio of one-side accumulated plastic deformations $\overline{e}_p^{(k)}$ to the local deformations at quasistatic tension rupture $\overline{e}_{pk}$ $\left( d_s = \frac{\overline{e}_p^{(k)}}{\overline{e}_{pk}} \right)$ and of the ratio of the accumulated number of cycles $N$ to the fracture number of cycles $N_{ef}$, according $d_f = N/N_{ef}$

$$d_f + d_s = 1. \quad (6)$$

Expression (3) of the cyclic stress-strain curve is used for the evaluation of the deformation state kinetics in the concentration zones, while Eqs. (6) are employed for the evaluation of the fatigue life in these zones at high temperatures.

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**Biographical Sketches**

**Nikolay A. Makhutov,** Professor, Dr.Sc. Member-Correspondent of the Russian Academy of Sciences. Head of the Department for Strength, Resource and Safety of Machines and Structures of the Mechanical Engineering Research Institute of the Russian Academy of Sciences (IMASH RAS).

Professional interests: Development and investigation of problems: strength, resource and engineering safety of complex technical systems; the theory and methods of the mechanics of catastrophes for engineering systems; the theory of risks; criterion of a nonlinear fracture mechanics; the mechanics of a non-isothermal deformation and fracture; means of mechanical tests for brittle strength, multi-cycle and low-cycle fatigue; the normative documentation on engineering safety, strength and resource of constructions.

*Professional activity:* 1976 - to the date - Head, Department for Strength, Resource and Safety of Machines and Structures, IMASH RAS, 1978 - to the date Head, Cyclic Plasticity Laboratory; 1992 - 1996 - Member, Bureau of the Department of problems in machine-building of the Russian Academy of Sciences; 1964 - 1976 - Researcher, IMASH RAS; 1959 - 1964 - Post-Graduate Student, Assistant at Moscow Aviation and Technology Institute.

*Other activity:* 1990 - to the date - President, CODAS Association (Complex Operation Diagnostics of Accident Situations); 1991 - to the date - Scientific Supervisor of the Federal Scientific, Research and Technology Program "SAFETY"; 1993 - to the date – Vice-president, Non-Governmental International Institute of Engineering Safety (IIES); 1976 – 1990 - Coordinator, the "STRENGTH" International Research Program; 1993 - to the date – the Russian Correspondent of the American Society of Mechanical Engineers (ASME International).

*Publications:* 15 Patents, 25 monographs, 420 scientific papers, 120 reports at international seminars and conferences.

**Mikhail M. Gadenin** Ph.D. Leading Scientist of the Department of Strength, Resource and Safety of Machines and Structures of the Mechanical Engineering Research Institute of the Russian Academy of Sciences (IMASH RAS).

*Professional interests:* Development and investigation of problems: strength, resource and engineering safety of complex technical systems; the equations of a state and criterion of accumulation of damages for conditions of a cyclic elastoplastic deformation; experimental definition of the characteristics of mechanical properties of materials at complex modes of a force and temperature loading; methods and means of experimental researches of mechanical properties of materials at service loading conditions; the normative documentation on calculations of strength and engineering safety parameters for materials and constructions.

*Professional activity:* 1987 - to the date - Leading Researcher, Department of Strength, Resource and Safety of Machines and Structures, IMASH RAS; 1969 – 1987 - Junior Researcher, Post-Graduate Student, Senior Researcher, IMASH RAS.

*Other activity:* 1983 - 1989 Reviewer, "MECHANICS" Review Journal, All-Russia Institute of Science & Technical Information; 1990 - to the date - Member of CODAS Association (Complex Operation Diagnostics of Accident Situations); 1993 - to the date - Scientific Secretary, Non-Governmental International Institute of Engineering Safety (IIES); 1970 - to the date Scientific Secretary of Scientific Seminar on Materials and Structures Strength named after Academician S.V.Serensen, IMASH RAS; 1995 - to the date - Member of the American Society of Mechanical Engineers (ASME International).

*Publications:* 14 monographs, 120 scientific papers, 30 reports at international seminars and conferences.