LOOK
ACADEMIC PUBLISHERS
OPEN ACCESS

INTERNATIONAL JOURNAL OF ENVIRONMENTAL & SCIENCE EDUCATION
2016, VOL. 11, NO. 17, 10211-10227

# Fundamental Studies of Strength Physics - Methodology of Longevity Prediction of Materials under Arbitrary Thermally and Forced Effects

Mark G. Petrov

Siberian Aeronautical Research Institute named after S. A. Chaplygin, Novosibirsk, RUSSIA.

**ABSTRACT**

Thermally activated analysis of experimental data allows considering about the structure features of each material. By modelling the structural heterogeneity of materials by means of rheological models, general and local plastic flows in metals and alloys can be described over. Based on physical fundamentals of failure and deformation of materials that are revealed by thermally activated analysis of simple test data, the methodology of longevity prediction of materials under arbitrary thermally and forced effects is considered. The methods of thermally activated analysis of strength tests results of duralumin and boron plastic are considered with regard to low temperature effects of failure. The correcting for the effective temperature that take account of these features, is been refined values of activated parameters of the process. Thermally activated analysis of experimental data should also take into account the quantum features of low-temperature fracture kinetics. In processing the experimental data, temperature correction is necessary to insert as it takes into account the low-temperature features of fracture, and in some cases changes the method of processing. It specifies the value of activation parameters of the process, which are used later in equations of physical warping and fracture kinetics under durability and longevity prediction of materials in constructions.

**KEYWORDS**
Physics of condensable state, rheology,
thermally activated analysis,
cryogenic temperatures, longevity of materials.

**ARTICLE HISTORY**
Received 3 June 2016
Revised 6 September 2016
Accepted 23 September 2016

## Introduction

Despite the multifaceted studies of material properties, currently there is no single concept, which would allow successfully meeting the challenges of evaluating strength and durability of constructions under rough field conditions. There are lot of works devoted to physical and metallographic aspects of strength and fracture (Petrov, 2015; Petrov & Ravikovich, 2001; 2004). They provide insight into what is happening in the material explaining the observed regularities of its response. However, the practice of constructions' strength and durability calculations usually is not related to this. There are many different approaches and methods for determining the bearing capacity of material

**CORRESPONDENCE** Mark G. Petrov ✉ markp@risp.ru, mark-st@ngs.ru

structures according to the nature of load and temperature, each of which is applicable only in a limited range of field conditions (Petrov, 2011; Leibfried, 1955; Samsonov, 1976). Expanding the range, problems arise devoted to composition of approaches. The difficulties appear as a response to the fact that the proper basis of solution is ignored, that what the material is actually itself (Wooten, 2013; Caner & Bažant, 2014; Bulat & Volkov, 2016). Even measurement units of durability are different in terms of loading: it may be time, or loading cycles, and sometimes the amount of loads (Vorobiev, Ol'kin & Stebenev, 1990; Petrov & Ravikovich, 2001; Salganik, 1970). Based on fundamental research in physics of condensed state an opportunity to review the traditional methods of assessing the strength and durability of constructions that are "in need of theoretical enlightenment and further clarification" (Sedov, 1976). Rethinking the properties of materials following the physical representations of strength and combining the methods of mechanics, physics and materials science, the problem of forecasting the bearing capacity of materials turns out well in complex by their nature temperature and power conditions and the external impact (Regel, 1974; Petrov, 2015; Petrov & Ravikovich, 2001).

Currently gained experience of a large amount of experimental data and existing theoretical work provides a reasonable basis for bringing all phenomena and laws observed at fracture into a coherent frame of references and developing new longevity prediction methods on that basis. It also requires a wide variety of modern technology field conditions.

Solving these problems is impossible without generation of new continuum models based on the physics and thermodynamics of internal processes in solids under load. Only the idea of a solid body as a physical medium allows considering over relation the processes of deformation and fracture, structural transformations, physical and chemical effects. Analysis of experimental data following these positions creates qualitatively new insights into the solids properties, allows the experiment to determine the optimal volume and sequence characterization of new materials, thereby reducing the cost and terms of constructional design (Petrov, 2015).

## Aim of the Study

Consider the physical processes of fracture and deformation in solids.

## Research questions

What is the impact of displaceable thermal and force conditions on longevity of materials and constructions?

## Method

The theoretical and methodological basis of the study was a complex of methods relevant to target goal, such as induction and deduction, abstraction and generalization, analysis and synthesis, analogy, as well as modeling. The paper describes the experience of leading domestic and foreign researchers, who studied this issue.

The empirical basis of the study was an experiment, in which the studied objects were placed in special, controlled and managed conditions. This method of obtaining knowledge allowed us to consider the characteristics of solids and measure the impact on them of different temperature values.

## Data, Analysis, and Results

Physical behavior of fracture and compressive plastic flow are identified in the simplest of experiments determining the longevity of materials and measuring the flow rate at constant temperature and voltage (Regel, 1974). Expression for longevity was obtained according to numerous experimental data of testing different materials in a structurally stable condition,

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma\sigma}{RT}\right) \tag{1}$$

as well as the rate of plastic flow (creep flow)

$$\dot{\varepsilon}_p = \dot{\varepsilon}_0 \exp\left(-\frac{Q_0 - \alpha\sigma}{RT}\right) \tag{2}$$

as a function of stress σ and absolute temperature $T$, where $U_0$ and $Q_0$ – the initial values of the activation energy (EA) of fracture and deformation, $\gamma$ and $\alpha$ – activation volumes (perturbation-sensitive modules), $R$ – moral gas constant. The pre-exponential multiplying factor $\tau_0 \approx 10^{-13}$ c, $\dot{\varepsilon}_0$ can be represented as the product of $\varepsilon_* \nu_0$ (Petrov, 1993), where $\varepsilon_*$ – permanent change of form under bar spitting fracture and $\nu_0 = 1/\tau_0$ – proper Debye frequency (Petrov, 1993).

An expression of the form (1) has a theoretical basis. It follows from thermodynamic equation of solid condition, at the same time linearity of longevity logarithmic dependence on force acting on the homopolar bond is confirmed by molecular dynamics method (Yushchenko, 1981). Parameter $\dot{\varepsilon}_0$ in the expression (2), written in terms of thermodynamics, is considered as entropy term effect on total effect of the deformation process component (Krausz, 1975). The $U_0$ value experimentally obtained for different materials correlate well with the energy of sublimation (Petrov, 1993). Physical interpretation of (1) and (2) parameters set before in (Petrov, 1993), allows suggesting the strength and deformation characteristics of the materials to be determined by their structure and thermal properties of included substances. Fracture and deformation consideration as a combination of internal thermodynamic process is the foundation of the fracture kinetic concept. It allows solving the problem of resistance, which based on current deformable solid mechanics approaches still are not solved.

(1) and (2) indicate that the absence of significant changes in the material's structure under plastic flow and fracture (continuance activation volumes) must comply with linearity dependence $U(\sigma) = U_0 - \gamma\sigma$ and $Q(\sigma) = Q_0 - \alpha\sigma$ in statistical field of $RT\ln(\tau\nu_0)$ and $RT\ln(\dot{\varepsilon}_0/\dot{\varepsilon}_p)$ values. Figure 1 shows the result of such 1201 T1 alloy test processing for thermal and force conditions, in which significant changes in material's structure are not observed (Petrov, 2015).

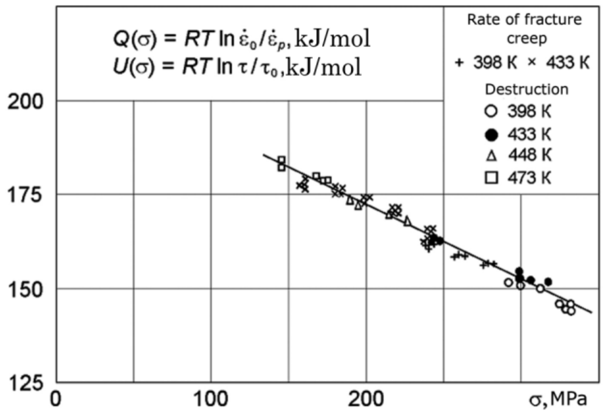


**Figure 1.** 1201 T1 alloy bar fracture and steady creep rate EA power dependence tested under constant temperature and load

Knowledge of physical nature of flow and solid fracture allows getting the strength characteristics of new materials with minimum cost. This is important at the designing stage, when any detailed studies of them have not been conducted. For example, alloy creep characteristics are required to determine under minimum amount of time for testing. If the material does not undergo substantial flow in the process of structural changes, the task is simplified. Indicating $A = \varepsilon_* \nu_0 \exp(-Q_0 / RT)$ and in (2) we have a differential equation of elastoplastic body deformation as the sum of rates of elastic deformation and plastic flow (Petrov, 2015),

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{M} + A\exp(B\sigma)\,, \tag{3}$$

in which $M$ – modules of elasticity accepted in rheology.

(3) solution under constant rate of deformation $\dot{\varepsilon} = C$ :

$$\sigma = -\frac{1}{B}\ln\left\{\exp[-B(\sigma_0 + MCt)] + \frac{A}{C}[1 - \exp(-BMCt)]\right\}, \tag{4}$$

where at the time t the stress from $\sigma_0$ to $\sigma$ do not depend on the size. At the initial moment when the stress is low, the first term in the logarithm is greater than the second one; the stress $\sigma$ is proportional to $Ct$ deformation. First term tends to zero ($t \to \infty$) under further increase of stress, so a "yield point" appears,

$$\sigma_y = -\frac{1}{B}\ln\left(\frac{A}{C}\right), \tag{5}$$

the value of which depends on the rate of deformation and temperature. In other words, deforming material in tests at a constant rate, we obtain the rate of creep, which is in congruence with a predetermined speed, because of the yield stress. Several values of yield stress may be obtained from one material bar increasing rate of deformation in stages.

Figure 2 shows a calculated diagram picture of aluminum alloy deformation according to equation (4) under three consecutive increases of the rate of deformation. The calculation is made for the duralumin at 448 K under values of

(3) experiment parameters (Petrov & Ravikovich, 2004). This method for determining the creep characteristics, which are illustrated by means of rheological model, has a copyright certificate (Polyak, 1973). After experimenting with several values of temperature, all three parameters that are included in (2) can be observed in equation (5). Under material's structural changes (when the parameter B is not constant), the flow is analyzed over time using solution (4), which determine its dependence on time and the amount of deformation. The same analysis algorithm is used for the study of structural changes in the material at the stage of transient creep (Petrov, 2015).

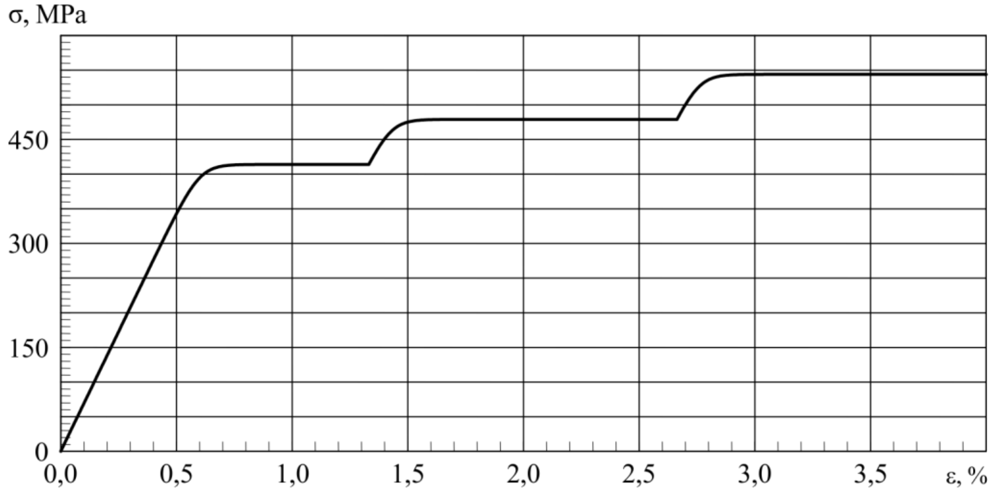


**Figure 2.** Calculated diagram of aluminum alloy deformation under consecutive increase of the rate of deformation

Strength characteristics of the material can be obtained similarly, but with minimum volume and time of the experiment. Bars from the selected lot are loaded at different temperature, each with its load rate or program (trajectory). Thermally activated analysis of experimental data is the next: time of loading $t_*$, and stress $\sigma_*$, under which comes macro-fracture of bar (the appearance of a crack, break or bar separation into parts). Power dependence of EA fracture is also the result of this experiment processing. However, the difference is that the $\sigma_*$ value called "resistance to rupture" is used as stress value; equivalent fracture time instead of longevity τ, calculated through the integral – rate of destruction in time. Rate of destruction is understood as an expression inverse longevity (1): $\dot{\omega} = 1/\tau$. If there are no significant structural changes under selected mode of material loading, experimental data fit into a single power dependence as EA fracture by direct determination longevity in the case of constant or monotonically increasing stress (Petrov & Ravikovich, 2004). Otherwise, the observed deviations from the $U_0 - \gamma\sigma$ line reveal thermally-force and thermally time changes in the field of material structures that require special analysis and modeling (Regel, 1974).

Assume that it is necessary to evaluate the strength properties of steel with different contents of alloying elements in different structure conditions. Using the mentioned above method, we shall lead bar testing monotonically loading each one at its temperature. Figure 3 shows the results of thermally activated analysis of obtained data.

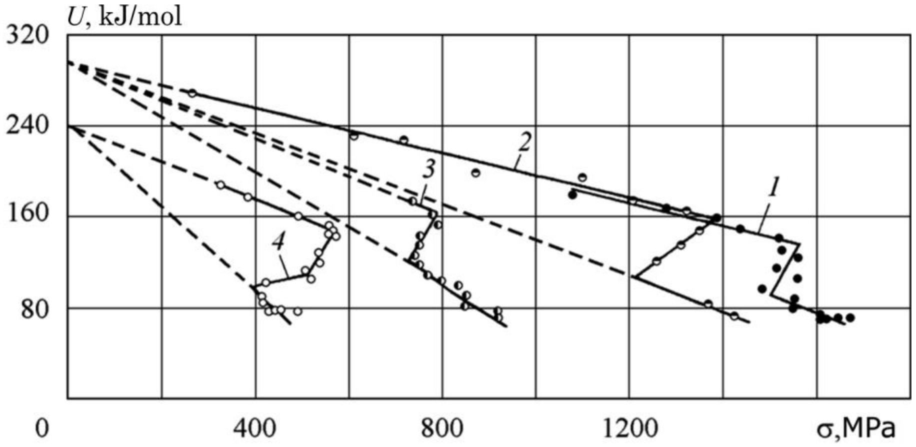


**Figure 3.** EA alloy fracture strength dependence based on α-iron under monotonically loading: *1* - steel 30CrGSNA, drawing-back 693 K (293–723 K); *2* - Steel 30CrGSA, drawing-back 783 K (293–873 K); *3* - Steel 30CrGSNA, drawing-back 973 K (293–683 K); *4* - Armco iron (293–723 K)

We can observe the similar qualitative feature of fractures in strength terms of activation energy, as in high-strength steels and technically pure iron. Then there is an area, where 30CrGSA and 30CrGSNA steels have practically identical strength characteristics. Effect of drawing-back temperature on strength properties of steel 30CrNSNA is visually showed. All three alloying steel types are almost identical in value of initial activation energy of destruction and change the activation volume in pre-specified range of values. In complementing these data, we can obtain more accurate activation parameters. Permanent change of form $\varepsilon_*$ must be measures in all cases. Its dependence on loading conditions is also a characteristic of material's structure and requires a separate description (Petrov, 2009).

Under variable repeated or little stresses that do not cause the total material flow, there is a fatigue fracture impossible to describe with one of perturbation-sensitive modules. Fracture time decreases in comparison with that, which would have been at total material flow – creeping. Fatigue phenomenon is associated with local plastic deformations, which arise from the structural heterogeneity of material characterized by stress distribution under loading (Regel, 1974; Petrov, 1993). Fatigue failure also occurs over time. Monitoring the crack growth kinetics in stress changing process confirmed that (Regel, 1974).

The structural heterogeneity of material can be displayed with the use of rheological models representing a continuous spectrum of internal stresses in the form of a discrete set of parallel of connected elements with the rheological type properties (3). In addition, adding structural elements with parallel connection of elastic body with the body of plastic flow to total material flow differential equation (3). This structural model will describe local plastic deformation and stress under material loading (Petrov, 2015). Each element with its activation volume $\alpha$ will correspond to a particular set of statistically uniform amounts of material with a close level of internal stress.

Local plastic deformations resulting under material loading lead to inelastic solid deformation appearance closely related to fatigue fracture (Golovin, 1980). Therefore, the calculation of micro-plastic deformation and establish their relationship with fracture processes with the use of rheological solid models will solve the problem of prediction the longevity of constructions under arbitrary thermally and force effects (Petrov, 2015), which cannot be solved with the use of traditional methods based on "cycle ideology" (Strizhius, 2012). Cycle is characteristic of construction’s loading, but not longevity. It has four parameters – average value, range, frequency and shape (trajectory of loading) – and can be played at different temperatures. These five loading conditions determine the longevity and impact on it. The number of cycles depends on fracture time (how much of them will happen during the process), namely, from a single parameter – frequency. It will not conform to longevity, because this "unit" turns out different in every case.

Cyclic loading as a basic experiment is necessary for inelastic material measurement. Defining the micro-plastic fractures’ contribution in the disclosure of inelasticity loop under certain parameters of loading cycle and temperature, the number of cycles that have passed during bar fracture, establish a relationship between deformation and fracture of material for each structural element of the model. The required experiment volume here can be minimized. Since the longevity logarithm is linearly dependent on the constant component of the loading cycle and the creep under fatigue failure, range of loading is sufficient to specify only two values of average stress cycle. A number of the required range values of loading is chosen according to range of inelasticity dependence – two for each area of growth (Petrov, 2015).

Assuming from the beginning that damage accumulation occurs simultaneously and independently in different parts of material structure, calculating damage on conventional structural elements and the material model are performed independently. It is better conformed to experiment than under summing up all damages of element in material models into a single measure (Petrov, 2015). As a result of calculation over time, the curve of material’s longevity under varying loads can be presented later in stress cycles, block loading programs, flight etc. One of the calculated fatigue curves in a traditional representation is shown in Figure 4. It is the enveloping curve of endurance for all structural elements in material model in the way typical for construction (Vorobiev, Ol'kin & Stebenev, 1990).

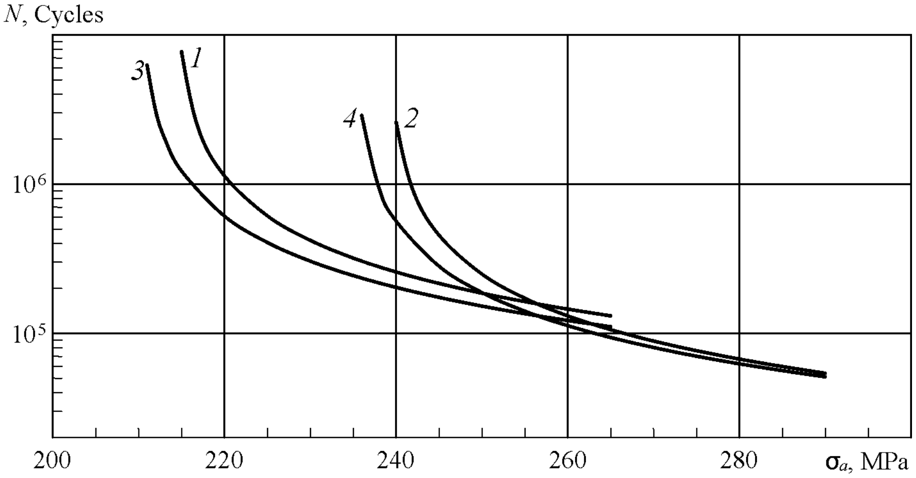


**Figure 4.** Calculated endurance dependence *N* of steel 09G2S from the range of stress $\sigma_a$ in terms of fracture probability 0.5 and frequency 10 Hz at average stress cycle equal to zero (*1, 2*) and 50 MPa (*3, 4*)

In general, thermally and force effects as random processes are characterized with spectrum. Having average spectral density of processes and their mutual statistical features it becomes possible to synthesize a near random process having discrete spectra with similar statistical features (Petrov, 2015). On the basis of differential equations' solutions that describe the rheological material properties the processes of its general and local plastic deformation are reproduced over time depending on the current temperature and stress, represented by piecewise linear implementations.

Evaluation of construction's longevity requires the calculation of local deformations and stress over time in zones of their concentration. The process of designing involves the selection of acceptable constructive decisions under the terms of required service life of constructions. Calculating the inelastic deformation and residual plastic material in critical points of construction, the operating stress is possible to be evaluated; therefore, the result of decision can be properly assessed. Rheological material models nested in calculated model of structural elements connecting the rated stress with local deformations also carry out such a function (Petrov, 2015). General circuit of material's longevity prediction in constructions are shown in Figure 5 (Petrov, 2011).

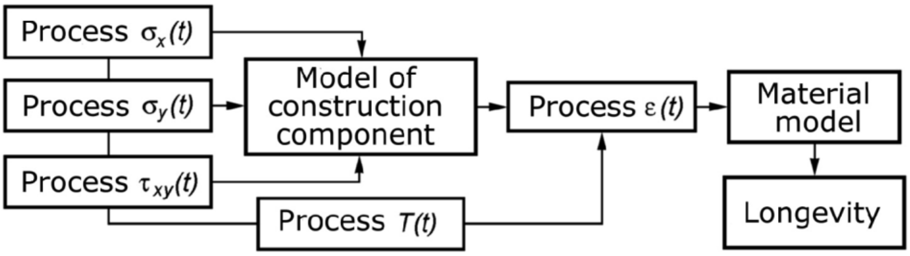


**Figure 5.** Circuit of estimated procedure of damage accumulation assessment in critical point of construction:

$\sigma_x(t)$, $\sigma_y(t)$, $\tau_{xy}(t)$ – mutually correlated loading processes in the form of nominal, normal and tangential stresses in critical point area,

$T(t)$ – temperature change in critical point over time,

$\varepsilon(t)$ – material deformation in critical point

The paper (Petrov, 2015) presents a line of calculated examples made under this circuit at constant load and temperature, thermos-mechanical loading under synchronized programs of thermally and force effects, random loading with different types of spectral density of current loads and different values of coherence function.

It is necessary to determine temperature ranges and exposure to stress environmental conditions in selecting materials for different field conditions, so their strength characteristics will be suitable for use in construction of any purpose. You must also be aware of changes in material's structure in desired range of field conditions that may limit it. As an example, extremely low temperature can be as dangerous as high. Both of them are determined by structural condition of material. The main tool is a thermally activation analysis revealing regularities of thermodynamic process of fracture, especially the material's structure and its changes.

Material has an effect on our belief what temperature should be considered as cryogenic. It is determined by the spectrum of thermal vibrations of atoms in solids (Leibfried, 1955). Lead's normal temperature is a high-temperature creep area (Θ = 106 K (Samsonov, 1976)) and boron fibers – cryogenic temperature (Θ = 1200-1400 K (Samsonov, 1976)). Therefore, we can say that each material has its own "normal temperature".

General relation providing that the materials' structure is not undergo substantial changes (1) expresses material's longevity under constant stress and temperature. In the case of temperature and stresses depending on time t, we should proceed from the average fracture rate $1/\tau$ to its current value (Petrov & Ravikovich, 2001).

$$\dot{\omega} = \nu_0 \exp\left(-\frac{U_0 - \gamma\sigma(t)}{RT(t)}\right). \tag{6}$$

Then the solid fracture process end (bar division into parts, appearance of macro-cracks) is calculated through the integral of rate of fracture over time (Petrov & Ravikovich, 2001):

$$\int_0^{t_*} \dot{\omega}(t,\sigma,T)dt = 1, \tag{7}$$

Where: $t_*$ – moment of fracture process end. If the material's structure changes, then you need to substitute the perturbation-sensitive module γ over time into (6) and (7) – $\gamma(t,\sigma,T)$.

One of the test methods used by us is that each bar of small lot tested at a specific temperature and loading program. As a result, strength characteristics of the lot are determined in the limited time at desired temperature and force range. Loading programs can be a variety of options for loading trajectory. This monotonous loading at given speed, loading at stages with constant time and power moves, cyclic loading with growing scale of stress or loading an arbitrary trajectory. The test results for each bar are digitized over constant time; thermally activation analysis is conducted based on obtained data. We can consider the range of temperature and pressure where the use of this material is assumed based on obtained EA values of fracture, as well as to determine the loading modes that cause structural changes in it. This method has been worked out on duralumin.

Linear dependence $U(\sigma) = U_0 - \gamma\sigma$ (EA force dependence of fracture) for duralumin is observed during long-term fracture (Figure 6a). Under rapid destruction EA fracture has form of a line (Figure 6b), but with the larger slope ratio $\gamma$ (Petrov & Ravikovich, 2001) interpreted as an increase in internal stresses when their relaxation speed is less than the rate of fracture.

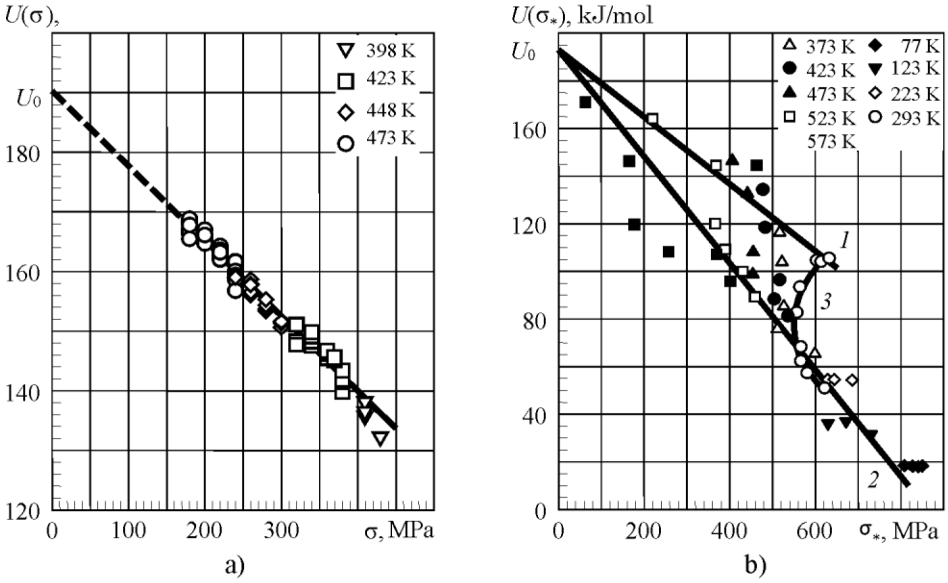


**Figure 6.** EA force fracture dependence of duralumin under constant (a) and growing at different speeds (b) loads: line *1* in Figure (b) corresponds to a straight line in figure (a sheet), averaged for a variety of fabricated products; *2* - fracture with the rate of 12.5-100 $s^{-1}$ (T ≥ 293 K) or under monotonous loading for 30 seconds (T ≤ 223 K); *3* - EA fracture dependence at 293 K over time in the range from 12.500 hours (match with line 1) to 0.01-0.001 s (match with line 2)

Determining EA fracture $U(\sigma) = RT\ln(\tau_{eq}\nu_0)$ value must be calculated through equivalent fracture time $\tau_{eq}$ that corresponds longevity under maximum stress $\sigma_*$ by equation (7) in certain loading program (Petrov & Ravikovich, 2001):

$$A\int_0^{t_*}\exp[B\sigma(t)]dt = A\tau_{eq}\exp(B\sigma_*),$$

where: $A = \nu_0\exp(-U_0/RT)$, $B = \gamma/RT$.

Monotonous loading at constant speed is more preferably under varying $\gamma$ value. In this case, the exponential dependence of stress fracture rate will make small errors in its definition under low $\sigma$, $\gamma$ value will largely correspond to the moment of maximum stress value. Such a test method and the interpretation of obtained data were also demonstrated at other aluminum alloys. (Petrov & Ravikovich, 2001).

At low temperatures ($T < \Theta$) the quantum statistics of vibrational state of atoms in solids should be taken into account (Salganik, 1970). For this purpose, the correction function is inserted into formulas (1) and (6)

$$F(T/\Theta) = \frac{1}{2N^2}\cdot\frac{\Theta}{T}\sum_{i=1}^{N} i\cdot\mathrm{cth}\left(\frac{i}{2N}\cdot\frac{\Theta}{T}\right), \qquad (8)$$

and multiplied by the absolute temperature. Where $N$ – number of atoms in the chain. According to the formula, function $F(T/\Theta) \to 1$ at $T > \Theta$ and $F(T/\Theta) \to 1/4\cdot\Theta/T$ at $T \to 0$. In other words, under absolute zero approximation $TF(T/\Theta)$ temperature value tends to a constant value (Leibfried, 1955) equal to a quarter of Debye. The validity of this amendment is verified by boron fibers test data (Sloutsker, 1983).

Correction function (8) at low temperatures was not considered in the work (Petrov & Ravikovich, 2001), so the maximum $\gamma$ value turned high. Therefore, the results of bar tests have been analyzed loaded with various combinations of loading rate and temperature giving the highest $\gamma$ value. The table shows the results of these data analysis, showing the magnitude of error by not taking into consideration the correlation for low temperature features of fracture. For correctness of comparison, we used test data of bars made of fabricated products of one type (rod). Each specified $\gamma$ value is averaged over 3-5 bar test data. The $\Theta$ value was assumed equal to 394 K as average for aluminum in the temperature range of 70-160 K (Leibfried, 1955). The $N$ value is taken equal to 100, where $F(T/\Theta)$ practically do not change to $N \to \infty$.

**Table.** Comparison of activation volume values calculated with allowance (and without it) for quantum affects under D16 T alloy bars' monotonous loading

| Temperature, K | Loading time, s | Fracture stress, MPa | Activation volume $\gamma(\theta)$, kJ/(mol·MPa) | Activation volume $\gamma$, kJ/(mol·MPa) |
|---|---|---|---|---|
| 523 | $9.3\cdot10^{-4}$ | 647 | 0.1956 | 0.1956 |
| 473 | $9.8\cdot10^{-4}$ | 686 | 0.1969 | 0.1969 |
| 473 | $9.6\cdot10^{-2}$ | 651 | 0.1900 | 0.1900 |
| 423 | $1.29\cdot10^{-3}$ | 663 | 0.1892 | 0.1896 |
| 373 | $9.6\cdot10^{-3}$ | 636 | 0.1943 | 0.1973 |
| 293 | $1.53\cdot10^{-3}$ | 763 | 0.1947 | 0.1986 |
| 293 | $1.12\cdot10^{-2}$ | 706 | 0.1947 | 0.1986 |
| 223 | 51.8 | 694 | 0.1956 | 0.2024 |
| 123 | 29 | 800 | 0.1986 | 0.2088 |
| 77 | 39.8 | 846 | 0.1969 | 0.2105 |

The average value $\gamma(\theta)$ was found to be 0.19465 kJ/(mol·MPa) with a standard deviation of 0.003, which does not exceed the usual error of its determination. Namely, activation volume indicating an absence of internal stress relaxation at relatively rapid fracture turns out constant. At lower test temperature ($T << \Theta$) neglect of correction provides errors in determining the $\gamma$ coefficient (at temperatures below 370 K). This will make mistakes in predicting the longevity of materials in constructions.

We note that duralumin is a typical nanostructured material. The size of fine precipitates – GP and GPB zones – is only few tens of nanometers (Petrov, 2015). The disintegration of supersaturated solid solution only increases the activation volume $\gamma$ without changing the $U_0$ value (Petrov, 2008). Any nanostructure will not give a significant increase in longevity under low stress. You need to take a different material to do this.

Another series of tests confirming the necessity of taking into account the effects of low-temperature fracture was carried out on born-fiber reinforced plastic bar at temperature range from 293 K to 423 K – a region of cryogenic temperature for certain material. We tested flakes of five-layer born-fiber reinforced plastic of three types of reinforcement with fiber diameter – 90 microns. Cross section of first group bars was 2.2×20 mm with reinforcement scheme [+45°/−45°/0°/+45°/−45°]. Cross section of second – 1.3×15 mm with reinforcement scheme [0°/90°/0°/90°/0°]. The third is different from the first one only in thickness – 1.7 mm due to the smaller proportion of binder. Bars were loaded with extension by different programs. Layers' orientation of 0° – flake's long axis angle, towards which the load was applied.

Firstly, pilot tests of bars from first and third groups were conducted at 293 K, bearing capacity of which was determined only by one axial-oriented fiber layer. Following the developed methods of analysis of any structure and material properties (Petrov, 2008), the bars were loaded cyclically in linear fashion with frequency of 0.25 Hz and increasing maximum load with its minimum zero value in each subsequent cycle. Inelasticity loop was recorded in each loading cycle, but in the last one – the load under bar splitting fracture usually not the maximum. The obtained data allows determining the stress values at which material properties should be studied. Figure 7 shows the amplitude dependence of inelasticity loop opening, through which you can select the stress amplitude for its fatigue longevity study. A maximum value of the load allows navigating in terms of stresses for static tests on longevity. Measurements were carried out on MTS-10 machine (range of ±1000 kgf) with the use of extensometer with the operational margin not exceeding ±2 micron/m.

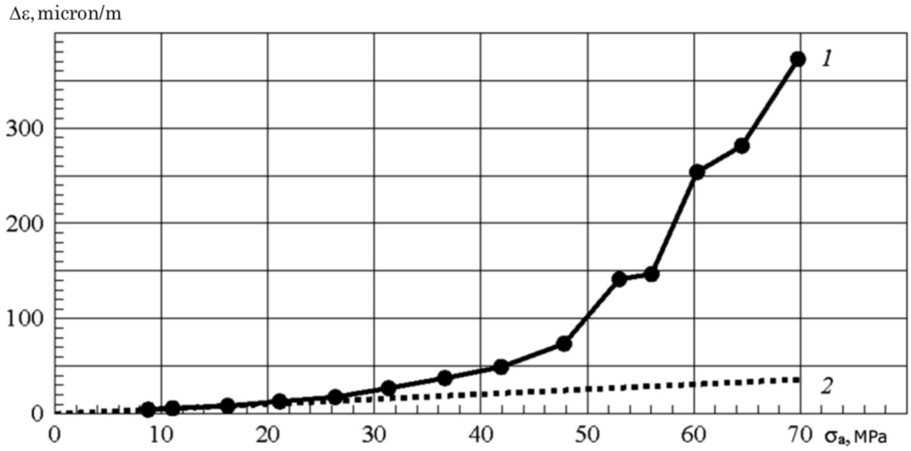


**Figure 7.** Dependence of inelasticity loop opening of five-layer born-fiber reinforced plastic flake (cross section 2.2×20 mm, reinforcement scheme [+45°/−45°/0°/+45°/−45°]) on stress amplitude under load with increase of maximum stress cycle in stages (293 K): *1* – amplitude dependence of inelasticity loop opening, *2* – amplitude dependence of loop opening at inelasticity of relaxation type

As with any material, the inelasticity only of relaxation type can be observed at low amplitudes, which is characterized by a pro-rata connection of loop opening with the stress amplitude or linear dependence of loop area on amplitude square or other methods of inelasticity measurement. Increasing stress amplitude, an additional inelastic deformation of hysteresis type appears indicating the local plastic flow occurring in different parts of material's structure. Fatigue fracture should be expected under these amplitudes (Petrov, 2008). However, in this case, non-uniformity of amplitude dependence of inelasticity loop opening unlike the metal alloys indicates local fractures of composite alloy as a part of the construction. At the same time, the maximum load was determined in the last cycle of loading; digitized implementation of stresses applied over time was used for thermally activated analysis. In most cases, bar splitting fracture was observed at discharging stages under stress lower than the maximum.

Further tests were carried out on second group bars by various loading programs at temperature 293 K, 323 K, 373 K and 423 K. Loading programs were subsequent. The first stage had 50 kgf or 400 kgf with duration of 120-600 s in the first case and from 15 to 63 hours in the second case. Than bars were loaded in a stepwise fashion with load of 50 kgf and the duration from 120 to 3600 s at each stage. Fracture time was register on the last stage (the amount of load and time of bar splitting fracture under transition to the next stage). Thermally activated analysis of obtained data was carried out after all these stages.

## Discussion and Conclusion

The difference in average stress discontinuity of bars obtained at each temperature was small in comparison with the range of variation of experimental data. Therefore, methods of experimental data treatment required changes, as the bar loading with any speed sets the destruction time varying within narrow limits. Stress of the process end is a random variable. Therefore, obtaining correct EA fracture dependence requires determination of strength $\sigma_*(U)$ where $U(\sigma) = RTF(T/\Theta)\ln(\tau_{eq}\nu_0)$ with future calculation of the inverse-rate of slope coefficient.

In processing the experimental data, we used the same value of temperature (Θ = 1300 K), evaluation of which was obtained in on fracture kinetics of boron fibers. The results of the analysis of thermally activated fracture of tested bars are shown in Figure 8; the types of fracture places – in Figure 9. Values $U_0$ = 576.8 kJ/mol, and $\gamma$ = 1.305 kJ/(mol·MPa) were obtained by means of $\sigma_*(U)$ dependence. The value $U_0$ within the scatter of experimental data coincided with its estimate obtained in (550 kJ/mol).

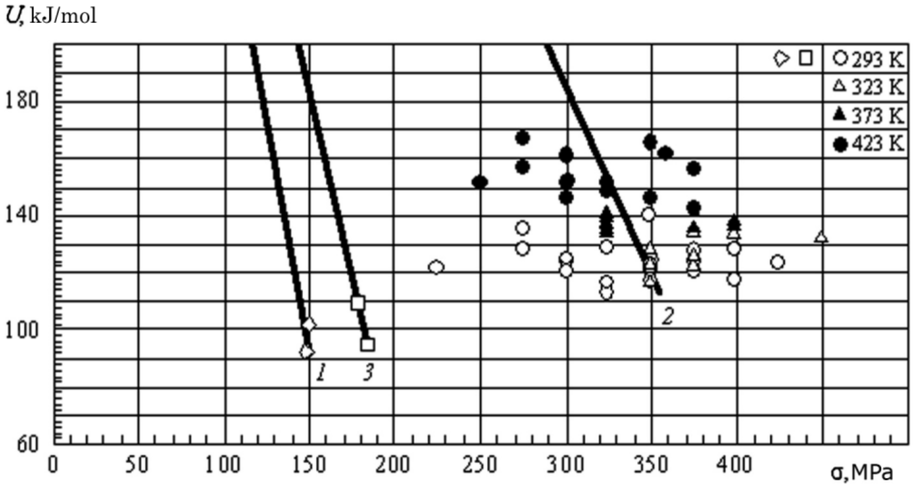
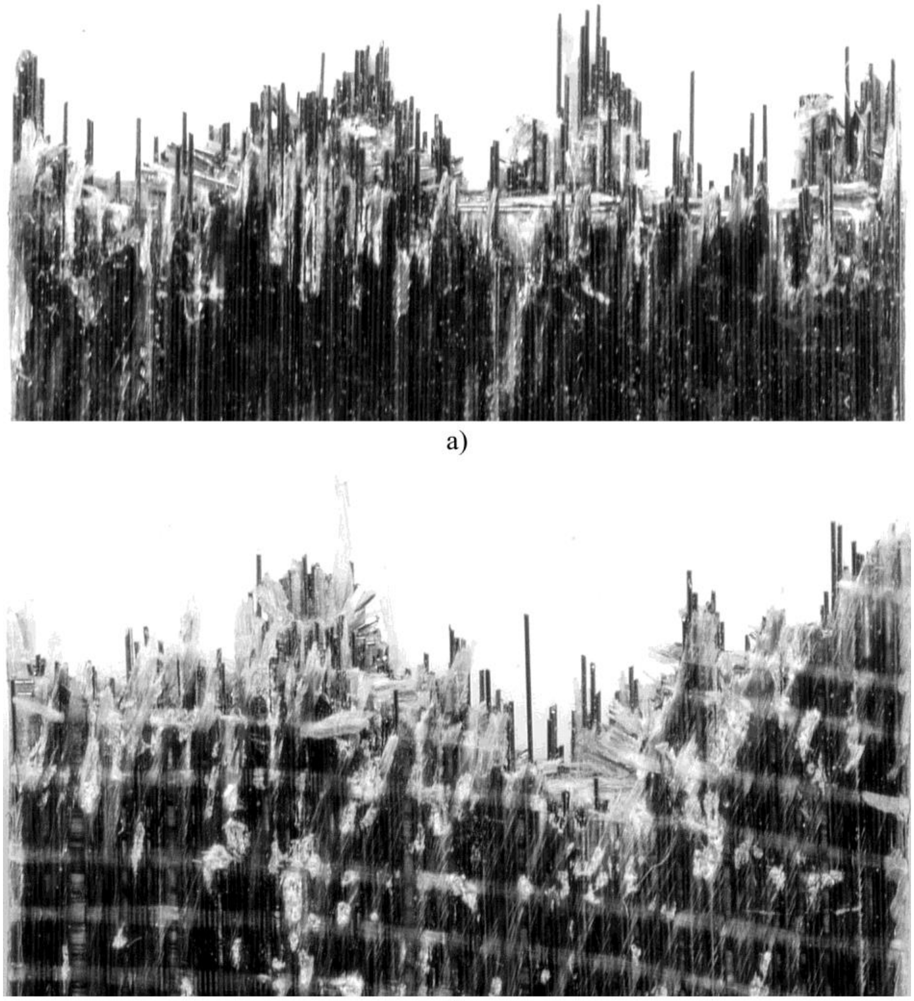


**Figure 8.** EA fracture strength dependence of five-layer boron-fiber reinforced plastic with varying shares of longitudinally oriented fibers: *1* - first group bars (293 K); *2* - second group bars (293-423 K); *3* - third group bars (293 K)

Quantities of perturbation-sensitive module γ for the first and third group bars are defined with the use of obtained value $U_0$. Cyclic loading with increasing stress scale had not given the large spread in longevity. There is a clearly visible difference between them, although it was tested in all three bars. Since these groups differed only in thickness due to differences in density of reinforcement, the calculation of elastic module in terms of the first cycle of loading (if inelastic deformations can be neglected) turned almost inversely proportional to coefficients $\gamma$: $\gamma_1/\gamma_3$ = 1.233, and $E_3/E_1$ = 1.259. The difference in the scheme of reinforcement of second group bars does not allow such a connection. For example, in relation to third group the increasing the number of longitudinally oriented layers reduces $\gamma$ in three times, in average – only twice, but the modulus of elasticity increases in 2.7 times.



a)

b)

**Figure 9.** Boron-fiber reinforced plastic bar tasted under 293 K (a) and 373 K (b), frontal view (zoom $10^{\times}$)

We note that the obtained value of activation volume γ quantitatively characterizes the material's structure in the field of destruction, namely, the level of internal stresses, which determine the rate of bar destruction. Value γ is associated with density of the reinforcement and the laying scheme of composite fibers, the ratio of the longitudinal and transverse bar sizes determine the loading of obliquely oriented fibers.

## Implications and Recommendations

Thus, knowledge of the physical processes regularity of fracture and deformation, resulting in fundamental physics research on strength as much as the construction of new continuum models on the basis of this knowledge allows solving the problem of forecasting materials' and constructions' longevity in a variety of displaceable thermal and force conditions. Thus, it becomes possible to select the optimum amount of experimental data necessary to understand the sequence of their receipt and possible to see the way of more detailed study and modeling of materials' properties.

Using the correction for the effective temperature, which takes into account features of low-temperature fracture, helps to clarify the activation process parameters. This extends the time-temperature range of applicability of physical kinetics equations for predicting the material's longevity problems in constructions. In addition to materials with high characteristic temperature, normal operating temperature range for which is in the area of cryogenic temperatures, the correct definition of activation parameters of the fracture process requires a change in the method of thermal activation analysis, if the test is conducted with the load increasing over time. This is especially important for composite materials having a large variation in strength properties, which are weakly dependent on the temperature of operation because of the small change of its effective value.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Notes on contributors

**Mark G. Petrov** is a PhD, Leading Scientist at the Laboratory of Strength of Materials and Structures, Siberian Aeronautical Research Institute named after S. A. Chaplygin, Novosibirsk, Russia.

## References

Bulat, P. V., & Volkov, K. N. (2016). Detonation Jet Engine. Part 1 – Thermodynamic Cycle. *International Journal of Environmental and Science Education, 11*(12), 5009-5019.

Caner, F. C., Bažant, Z. P. (2014). Impact comminution of solids due to local kinetic energy of high shear stress rate: II–Microplane model and verification. *Journal of Mechanics and Physics of Solids, 64,* 236-248.

Golovin, S. A. (1980). *Micro-plasticity and fatigue of metals*. Moscow: Science.

Krausz, A. S. (1975). *Deformation kinetics.* N. Y.: John Wiley and Sons.

Leibfried, G. (1955). *Microscopic theory of mechanical and thermal properties of crystals*. Berlin-Göttingen-Heidelberg: Springer-Verlag.

Petrov, M. G. (2008). Methods of analysis and diagnostics of structure and properties of materials produced under various technological processes. *XIV International conference on the methods of aerophysical research. Section V. Methods of aerophysical research in interdisciplinary problems and advanced technologies* (Paper 24). Novosibirsk: ITAM.

Petrov, M. G. (2009). Cracking of metal supersaturated solid solutions happening under fracture of a precipitation hardening aluminum alloys. *Journal of Fundamental and Applied Materials: materials of VI International Scientific School-Conference* (pp. 203-209). Barnaul: Altai State Technical University.

Petrov, M. G. (2011). Calculation-experimental method of resource consumption evaluation of dynamically loaded constructs. *Problems of optimal design constructions: reports of the second Russian Conference* (pp. 296-307). Novosibirsk State University of Architecture and Civil Engineering.

Petrov, M. G. (2015). *The strength and longevity of structural elements: an approach based on material models and physical environment*. Saarbrücken: Lambert Academic Publishing.

Petrov, M. G., & Ravikovich, A. I. (2001). Kinetic approach to prediction of the life of aluminum alloys under various thermally temporal conditions. *Journal of Applied Mechanics and Technical Physics, 42*(4), 725-730.

Petrov, M. G., & Ravikovich, A. I. (2004). Deformation and fracture of aluminum alloys following kinetic concept of strength. *Journal of Applied Mechanics and Technical Physics, 45*(1)*,* 124-132.

Petrov, V. A. (1993). *Physical basis of forecasting the longevity of structural materials*. St. Petersburg: University of Technology Publishing.

Polyak, L. Z. (1973). *Method for determining the characteristics of metals' rate of creep.* Patent №390,409 of the USSR / №1006825/25-28; appl. 04/26/1965; publ. 07.11.1973, Bulletin №30, priority 04.26.1965, 2.

Regel, V. R. (1974). *The kinetic nature of solids' strength*. Moscow: Science.

Salganik, R. L. (1970). Fluctuation mechanism of fracture. *Journal of Solid Physics, 12*(5)*,* 1336-1343.

Samsonov, G. V. (1976). *Properties of elements* (In 2 volumes, Vol I. Physical properties. Directory). 2nd edition. Moscow: Science.

Sedov, L. I. (1976). On perspective directions and problems in continuum mechanics. *Journal of Applied Mathematics and Mechanics, 40*(6)*,* 963-980.

Sloutsker, A. I. (1983). Quantum features of low-temperature fracture kinetics of boron. *Journal of Solid Physics, 25*(3), 777-783.

Strizhius, V. E. (2012). *Methods for calculating fatigue longevity of elements in air constructions*. Moscow: Science.

Vorobiev, A. Z., Ol'kin, B. I., & Stebenev, V. N. (1990). *Fatigue resistance of constructional elements*. Moscow: Science.

Wooten, F. (2013). *Optical properties of solids.* New York: Academic press.

Yushchenko, V. S. (1981). Molecular dynamics modeling under research of mechanical properties. *Journal of Physicochemical Mechanics of Materials, 17*(4), 46-59.