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MATERIALS IN EXTREME CONDITIONS, THE CRITICAL PHENOMENA AND PHASE TRANSFER IN THE DYNAMIC DESTRUCTION

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ABSTRACT

At present acute is determining of the possibility of modeling of matter behavior under extreme conditions with the aid of knowledge of samples behavior under laboratory conditions. The paper discusses metals behavior under extreme conditions on the basis of study of dynamic failure under powerful penetrating radiation pulses.

A complex approach to determining of qualitative characteristics of behavior of a number of metals and metal *Pu* on different time and scale levels is based on application of: methods of quantitative fractography using special package of mathematical programs of interactive system of image analysis; methods theory of fractals and theory of percolation, body of mathematics of critical phenomena theory.

There was expanded the area of study of non-equilibrium matter state in sub-nanosecond longevity range ($t \sim 10^{-9} \div 10^{-11}$ *s*) under the action of ultra-short pulses of laser radiation.

Hierarchy of scale and time levels of dissipative structures arising in the processes of dynamic metals failure under different kinds of pulse action was established. There is shown similarity of dissipative structures behavior on different scale levels formed under external pulsed action, what means scale invariance in the system behavior and independency of occurring processes on the system size.

Two dynamic invariants J_1 and J_2 were determined which allow forecasting of metal *Pu* behavior in coordinates *T, P, t* in the longevity range $t \sim 10^{-6} \div 10^{-10}$ *s*, in the initial temperature range $T_0 \sim 4K \div 0{,}8\, T_{melt}$.

The above-mentioned specifies the possibility of applying ultra-short pulses of laser radiation for a study of properties, for example, metal *Pu* under extreme conditions and determines universal metals behavior in the dynamic failure phenomenon.

Key Words: critical phenomena and phase transfer, dynamic destruction, extreme conditions, quantitative fractography, theory of fractals, theory of percolation.

1. INTRODUCTION

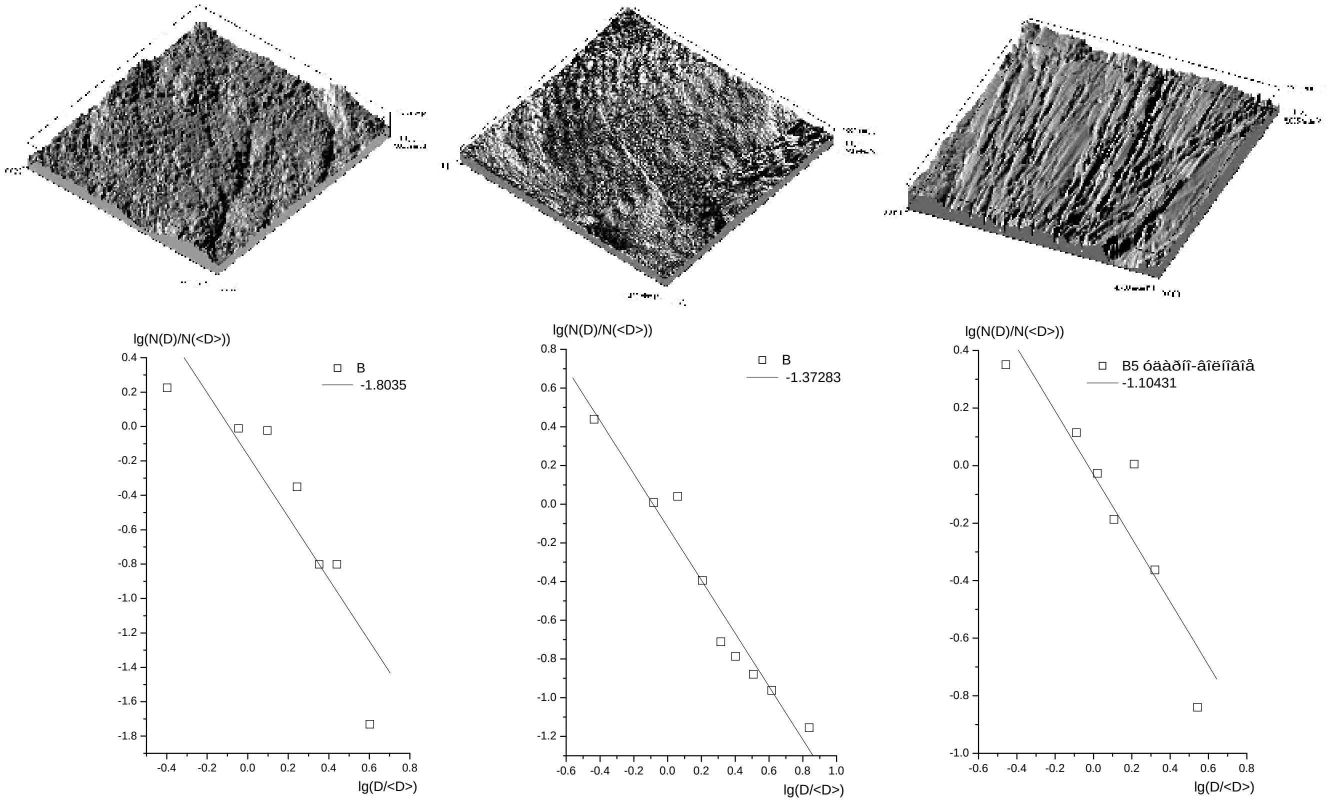
In a study of metals behavior under extreme conditions at different types of pulse action the priory methods for the study of dynamic failure process are methods of explosive and shock-wave loading (longevity $10^{-5} < t < 10^{-8}$ s), action of high-current beams of relativistic electrons (HCBRE) (longevity range $t \sim 10^{-6} \div 10^{-10}$ s) as well as in sub-nano second range ($10^{-9} \div 10^{-11}$ s) effect of ultra-short pulses (USP) of laser radiation with power density J of laser radiation up to $J \sim 10^{14}$ W/cm^2 [1-3].

At the amplitudes of pulse pressure of units-hundreds kilobar in the longevity range $t \sim 10^{-6} \div 10^{-10}$ s evolution of micro- and meso-scopic defects in the phenomenon of dynamic failure is determinative in common regularities of metals invariant behavior under the action of powerful penetrating radiation pulses (initial temperature range $T_0 \sim 4K \div 0.8\ T_{melt.}$, energy input rate $dE/dt \sim 10^6 \div 10^{12}$ K/s, absorbed energy density $10 \div 10^4$ J/g).

2. MATERIALS IN EXTREME CONDITIONS

Priority methods for description of unique phenomenon of dynamic failure are methods of nonlinear physics that allow determining of universal attributes of evolution of non-equilibrium systems conditioned by collective effects, self-organization phenomena in the arising dissipative structures [1, 2]. As a result of conducted studies [2] there was established a hierarchy of scale and structure levels of dissipative structures determining the process of dynamic metals failure that reveals in nonergodic behavior of hierarchical systems in the dynamic failure process.

2.1. Quantitative Characteristics of Dissipative Structures on Different Scale Levels



a b c

D – roughness size; <D> - average size of roughness;
N(D), (N(<D>)) – number of roughness of size D (<D>)

Figure 1. Scanning tunnel microscope (STM) -images of roughness of failure center inner surface (nano-level of investigations) of copper samples and fractal dimensions under the action of laser radiation USP (a), HCBRE (b) and those of a steel sample after shock-wave loading (c).

To determine quantitative characteristics of dynamic metals failure process – dissipative structures on different scale levels, such as: roughness of inner surfaces of failure centers (nano-scale level), cascade of crystal lattice slipbands (meso-level I), clusters – failure centers cascade (meso-level II), roughness of failure surface (macro-level), there were applied modern methods of quantitative fractography using modern packages of mathematical programs of image analysis interactive system (IAIS), as well as methods of modern digital microscopy [4].

Fig. 1 gives an example of treatment of roughness of failure center inner surfaces affected by HCBRE, laser radiation USP and shock-wave loading with the aid of IAIS

One of the evidences that the system is a percolation cluster is growth of “mass” of system M on the lattice parameter size l, covering (for example, in the two-dimensional case) the system from the law $M(l) \sim l^{-df}$, d_f - index corresponding to fractal dimension. As a result of conducted studies [3, 4] it is shown that roughness of inner surfaces of failure centers arising as a result of effect of laser radiation USP, HCBRE and at shockwave loading on the nano-scale level is a percolation cluster, for the structure element mass is growing depending on the lattice parameter size [3,4].

2.2. Mathematical Modeling of The Arising Cascade of Failure Centers

For adequate mathematical modeling of the arising cascade of failure centers, which is a percolation cluster at threshold of macro-failure, there is applied a model of lattice gas [3, 4]. A canonical distribution function in Ising model is similar to the function of grand canonical distribution in the lattice gas model that earlier was applied for adequate modeling of the arising failure centers cascade which is a percolation cluster at threshold of macro-failure. Topology phase transition – origin of coherence in the infinite percolation cluster is similar to critical phenomena.

This shows the analogy between the ferromagnetic Ising model and the lattice gas model [5, 7]. Distribution function of Ising model takes the form [5-7]

$$Z_i = \sum_s exp\left(\frac{J}{kT}\sum_{i,j} s_i s_j + \frac{\mu H}{kT}\sum_{i=1}^{N} s_i\right), \qquad (1)$$

where J- metabolizable energy; μ - Bohr magneton; H – field intensity.
Distribution function for lattice gas [5-7] is

$$Z = \sum_e exp\left(lnz \sum_{i=1}^{n} e_i + \frac{J}{kT}\sum_{i,j} e_i e_j\right) \qquad (2)$$

If one makes a substitution $e_ie_j = 1/4\, s_is_j + 1/4(s_i + s_j) + 1/4$, we receive the expression (1). Relations (1) and (2) show the analogy between the ferromagnetic Ising model and the lattice gas model. Phase transition into the ferromagnetic state as well as topology phase transition – origin of coherence in the infinite percolation cluster of failure centers cascade, is similar to critical phenomena.

Earlier it was shown [1, 2] that distribution of dissipative structures of roughness of inner surfaces of failure centers, cascade of crystal lattice slipbands, failure centers cascade, roughness of failure surface arising in the course of dynamic failure follow the expression of the type $N(D_i) \sim D_i^{-\alpha}$.

The similarity theory, i.e. knowledge of generalized variables for the given process, plays an important role when studying complex phenomena. So, for example, a statistical sum of failure centers cascade arising under the action of high-current beams of relativistic electrons and ultra-short pulses of laser radiation are similar.
The statistical sum, for example, of failure centers cascade arising under the action of HCBRE is

$$w_i = N_i/N_{tot} = A(D_i)^{-\alpha}; \tag{3}$$

$$Z = A\sum_i A(D_i)^{-\alpha} = A\sum_i a^{-\alpha} a^i D_1 = Aa^{-\alpha}\frac{a^N - 1}{a-1}, \tag{4}$$

α - fractal dimension [4].

Expression (3) and (4) is also true for the failure centers cascade formed under the action of laser radiation USP and for determining of statistical sum of “roughness” of failure surface mountain relief (macro-level) and failure centers inner surface (nano-level).

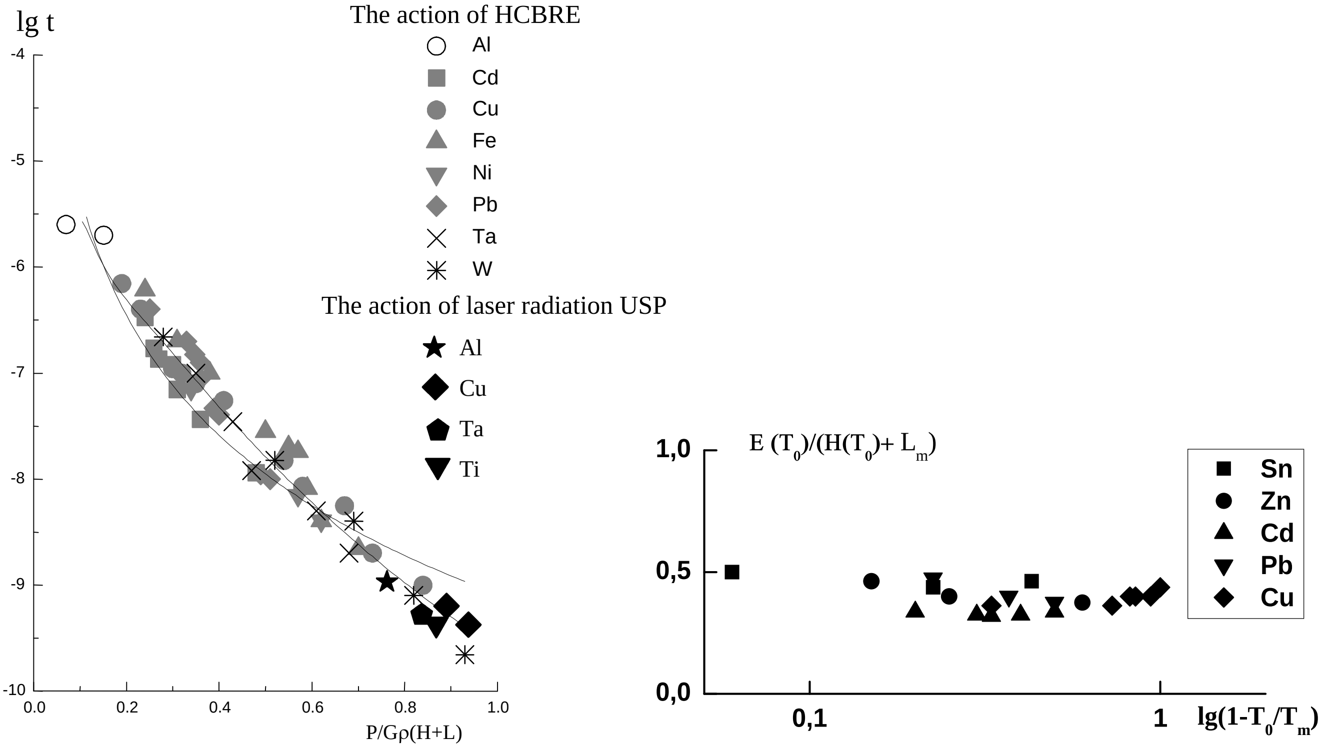
Phase transitions are a problem of many bodies when cooperative phenomena of the system elements play the main role. In the behavior of the system near the critical point not the specific law of particles interaction comprising a system, but a statistical nature of the system plays the main role. Modern concepts of critical phenomena theory are based upon the similarity hypothesis. This means scale invariance in the system behavior and independency of the occurring processes in the system on the system size, i.e. identity of behavior of dissipative structures formed under the external action on the structural materials on different scale levels.

2.3. Dynamic Invariants in The Longevity Range $t \sim 10^{-6} \div 10^{-11}$ s, $T_0 \sim 4K \div 0.8\ T_{melt}$

To each hierarchy level of dissipative structures indicated earlier corresponds its own value of potential energy U_i that is characterized by its parameter of the order n_i, distribution function f_i and the time of relaxation t_i. From the mathematical point of view description of each level of dissipative structures is rather a laborious process [2, 4]. That is why the main aim of the study of quantitative characteristics of dynamic failure process when macro-failure arises and changes the body coherence (topology transition) is establishing of unique, universal potential U of the whole system [2]. Papers [1-4] show, that $U = \sum_{\mathbf{i}} U_i = H + L_m$, where H - enthalpy and L_m – melting heat. There was established a dynamic invariant in the longevity range $t \sim 10^{-6} \div 10^{-11}$ s, $T_0 \sim 4K \div 0.8\ T_{melt}$, allowing determination of the time law of the ratio of absorbed energy (P) critical density causing failure, to energy parameters of crystal lattice:

$J_1 = \frac{P}{G\rho\left(H + L_m\right)}$, where G – Gruneisen parameter, ρ - material density. Dynamic invariant J_1 has close values for all studied materials [1, 2, 4] (see Fig. 2, a).

Basing upon determined time-temperature relationships (individual for each metal) by calculation-and-theoretical way there were received data on the interfacial failure in the longevity range $t \sim 10^{-6} \div 10^{-11}$ s, $T_0 \sim 4K \div 0.8\ T_{melt}$, in coordinates longevity t, dynamic invariant J_1 (see Fig. 2, a) and in coordinates $E(T_0)/(H(T_0) + L_m)$ and J_2, where $J_2 = lg\ (1\text{-}T_0/T_{melt})$ – the second dynamic invariant of a number of metals (see Fig. 2, b) [1, 2, 4].



a b

Figure 2. Time law of dynamic failure process (a); data on temperature laws of a number of metals presented in the universal coordinates (b).

Let us note that critical density of the absorbers energy causing failure, for example, of metals Ti, Al, Ta, Cu under the action of laser radiation USP and HCBRE agrees (see fig.2, a) [4].

2.4. Prediction of Behavior of *Pu* in The Longevity Range $t \sim 10^{-6} \div 10^{-10}$ s

In order to predict behavior of elements, units and structures from δ-alloy *Pu,* one should know quantitative characteristics of the system (structure) response on different scale levels at different time moments of external load action.

A unique mechanism of dynamic metals failure – lost of system (sample) coherence through clustering of failure centers cascade – unique order parameter and equal dimension of space where the process flows determine the possibility for predicting of metals behavior under extreme conditions.

Data of Fig.3 show an analogy of mechanism of slabbing stratification of samples from aluminum and δ - alloy *Pu*, which is related to the formation of slabbing zone under dynamic action [8].

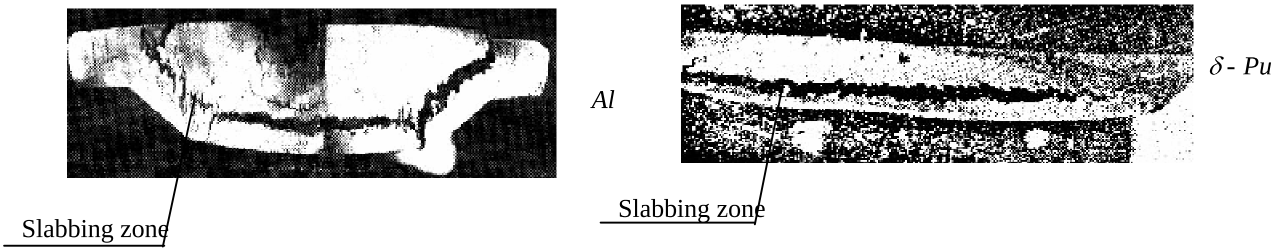
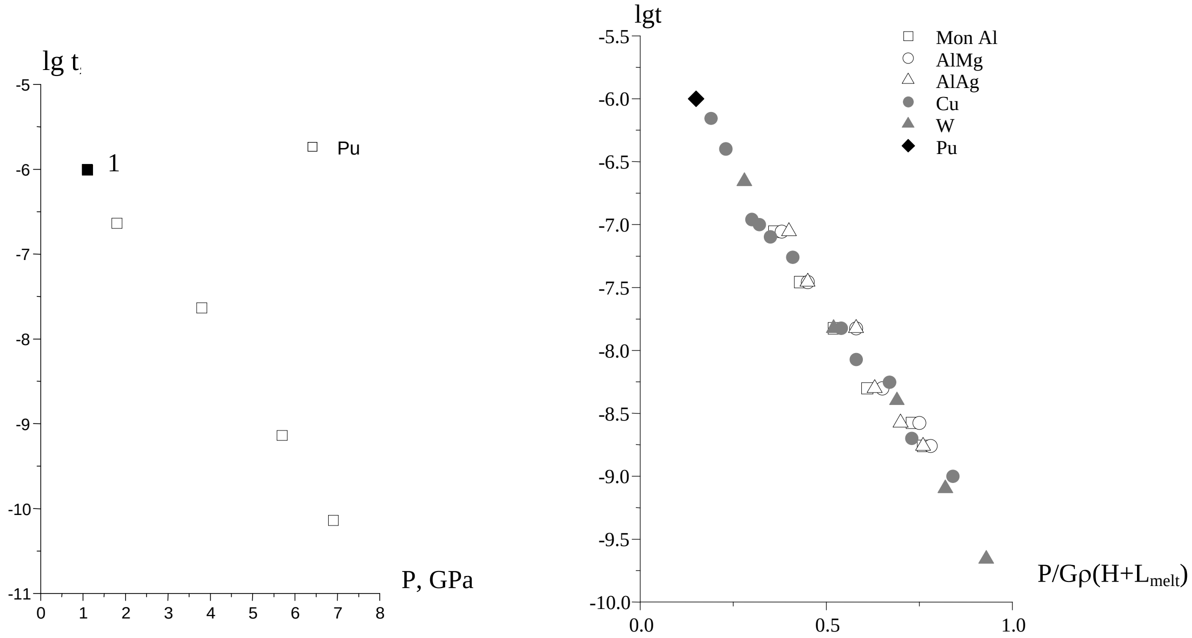


Figure 3. Analogy in the mechanisms of slabbing failure of Al and δ - alloy Pu.

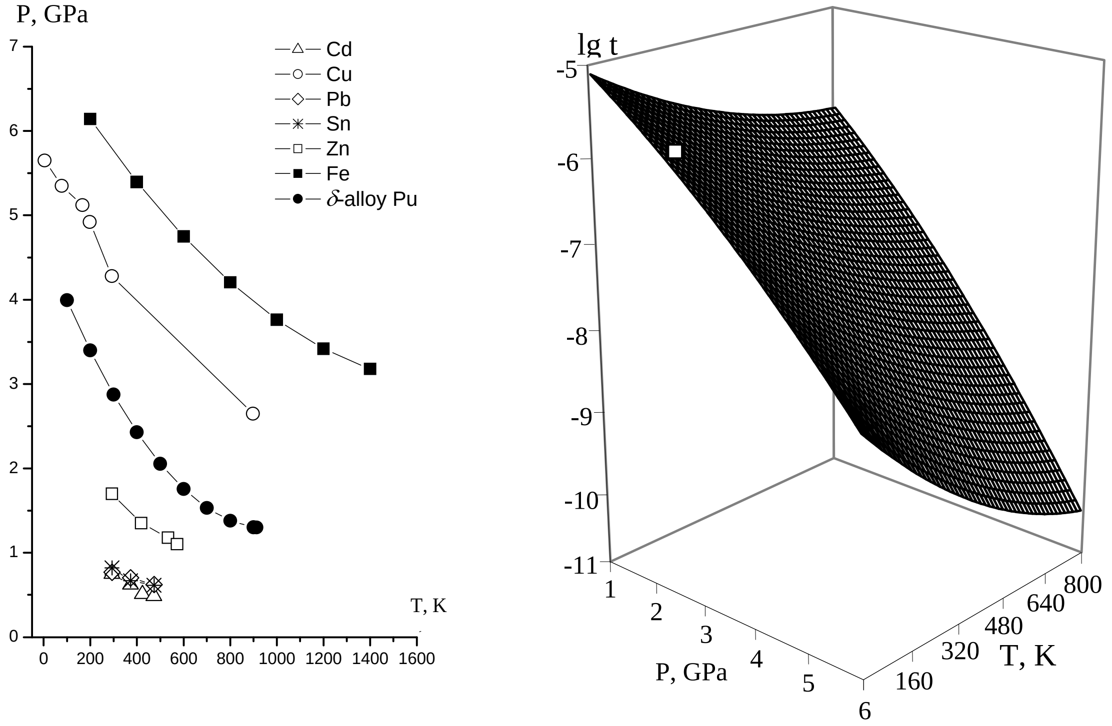
Paper [9] gives the values *H* and *L* for *Pu*, which allow prediction of behavior of *Pu* in the longevity range $t \sim 10^{-6} \div 10^{-10}$ s. Fig 4, a presents a longevity curve *Pu.* Point 1 was taken from paper [8], the rest points were predicted on the basis of the longevity curve [1, 4], presented in Fig.2, a. Fig. 4, b presents data on longevity of a number of metals and alloys.



a **b**

Figure 4. Data on longevity Pu (1- data of paper [8]) (a); data on time laws for a number of metals, presented in the universal coordinates (b).

By calculations taking into account results, given in Fig. 2, b, there was received a temperature law of negative pressure causing a failure of δ - alloy *Pu* sample. The obtained temperature law of the value of negative pressure causing the failure of a sample of δ- alloy *Pu* is given in Fig.5, a with temperature laws obtained earlier for *Cu*, *Sn*, *Pb*, *Cd* and *Zn*.



a b

Figure 5 –Temperature laws of negative pressure of a number of metals causing sample failure ($t \sim 8{\cdot}10^{-8}$ s) (a); plutonium dynamic failure surface (markers – experimental data [8]) (b).

On the basis of results of research mentioned above, there were built failure surfaces for *Fe* and δ-alloy *Pu* in the coordinates longevity t, pressure P, temperature T in the ranges: $T \sim 77 \div 913$ K, $P \sim 39.166 \div 2.747$ kbar, $t = 10^{-6} \div 10^{-10}$ s – for *Pu* (see Fig. 5, b); $T \sim 200 \div 800$ K, $P \sim 7 \div 1$ kbar, $t = 10^{-6} \div 10^{-10}$ s – for *Fe*.

Surfaces in the mentioned coordinates determine the boundary above which there is the failure area.

3. CONCLUSIONS

On the basis of complex approach in the work there was grounded the possibility of obtaining the quantitative characteristics of behavior, for example, of metal *Pu*, structural materials in the extreme conditions on the macro-level basing upon analysis of quantitative characteristics of dissipative structures arising on different scale levels, whose behavior is similar to critical phenomena.

The above mentioned determines the scale-invariant properties of dissipative structures behavior and conditions universal metals behavior in the dynamic failure phenomenon on the different time intervals at different amplitude–time characteristics of the external action and determines the possibilities of modeling of the matter behavior under extreme conditions (field observation) with the aid of samples behavior knowledge under the laboratory conditions [1, 2, 4].

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