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THE UNIVERSAL PROPERTIES OF METALS' BEHAVIOR IN THE DYNAMIC DESTRUCTION PHENOMENON IN A WIDE RANGE OF LONGEVITY UNDER THE INFLUENCE OF THE HIGH-POWER PULSES OF THE PENETRATING RADIATIONS

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ABSTRACT

The invariants of metal behavior in dynamic fracture (t~10^{-6}-10^{-10}s longevity range) have been found. The dynamic invariant allows the behavior of untested metals and alloys to be predicted under extreme conditions and new alloys resistant to certain types of pulse effects to be constructed using numerical methods.

Key Words: Thermal shock (TS), quasi-static and dynamic longevity ranges, dissipative structures, fractographic studies, percolation cluster, universal coordinates.

1. INTRODUCTION

The response of the metal on the exterior physical-mechanical action is defined both by its thermodynamic state, and also by the characteristics of the loading process.
The fracture phenomenon can be conventionally divided into two ranges. The quasistatic range of longevity $t > 10^{-4}$ s and the dynamic range of longevity $t < 10^{-6}$ s.

During thermal shock (TS) caused by high-current relativistic electron beams, which is detailed in [1-3], the fracture process proceeds within $t < 10^{-8}$ s time in contrast to conventional loading methods. The energy introduction time is $dT/dt \sim 10^{12}$ K/s and the temperature changes up to T_{melt}. It allows to reveal the temperature-time regularities of the process more completely, as the influence of the real structure of the crystal lattice in these test conditions is insignificant. Thus the results of these investigations provide the additional information on the concrete materials behavior and have a self-maintained value for the physics of fracture, including for the build-up of the fracture models at a high-speed deformation.

2. TEMPORAL REGULARITIES OF THE DYNAMIC FRACTURE OF SOME METALS

The research of the regularities of the dynamic fracture of some metals from $z \sim 13 \div 92$ (*Al*, *Ti*, *Ta*, *Ni*, *Pb*, *Cu*, *Mo*, *Cd*, *Sn*, *Zn*) in the longevity range $t \sim 10^{-6} \div 10^{-10}$ s, in the base temperatures range $T_0 \sim 4\text{K} \div T_{melt.}$, with the tempo of the energy input $dT/dt \sim 10^6 \div 10^{12}$ K/s ($dE/dt \sim 10^5 \div 10^{11}$ J/g·s), $dE/dm \sim 1 \div 10^4$ J/g was conducted. The received results are presented in the Table I.

Table I. Temporal regularities of the dynamic fracture of some metals

The metal	P, GPa				
	$t=10^{-6}$ s	$t=10^{-7}$ s	$t=10^{-8}$ s	$t=10^{-9}$ s	$t=10^{-10}$ s
Cd	0.54	0.76	1.12		
Ni	3.48	5.82	9.68	14.4	
Ta	4.96	7.47	10.87	15.0	
W		9.0	14.9	21.35	25.25
Fe	4.61	7.98	12.09	18.8	
Cu	1.66	3.77	6.99	10.21	
Pb	0.37	0.7	1.0		
Ti	2.13	4.93	10.42	14.0	
Sn	0.61	0.76	1.34		

It is obvious, that the forming of the data bank on dynamic strength, based on the handling of the gained particular regularities is not optimum. The basic objective is to find general regularities in the metals behavior, which are invariants with respect to the changes in the external environments. It is shown [1-3], that the resistance to the exposure in the phenomenon of the metals dynamic fracture puts up the dissipative structure appearing in the solid which is the fracture centers cascade. The use of the method of the spectral size distribution of the fracture centers at the various stages of the process allowed to determine the general regularities of the fracture center cascade formation.

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3. CORRELATED BEHAVIOR AND INITIATION OF SELF-ORGANIZATION OF THE FRACTURE CENTERS

The size distribution of fracture centers for various materials in the sections of loaded samples, which is presented in $lg(D/<D>)$, $lg(N(D)/N(<D>))$ coordinates, is produced by the similarity conversion [1-3]. This testifies to the fact that the process of dynamic fracture in metals proceeds within one primary process – accumulation and growth of fracture centers, which is accounted for by the basic part of longevity. Spectral size distribution of fracture centers has the form $N(D) \sim D^{-\alpha}$, where D is the fracture center size, $\alpha > 1$ (Fig.1, a). The fracture centers accumulation rate may be described by the evolution equation (Fig.1, b) of $dN/dt \sim N^{\beta}$, $\beta > 1$ type. The data given in fig.1 show correlated behavior and initiation of self-organization of the fracture centers cascade within the destructed sample.

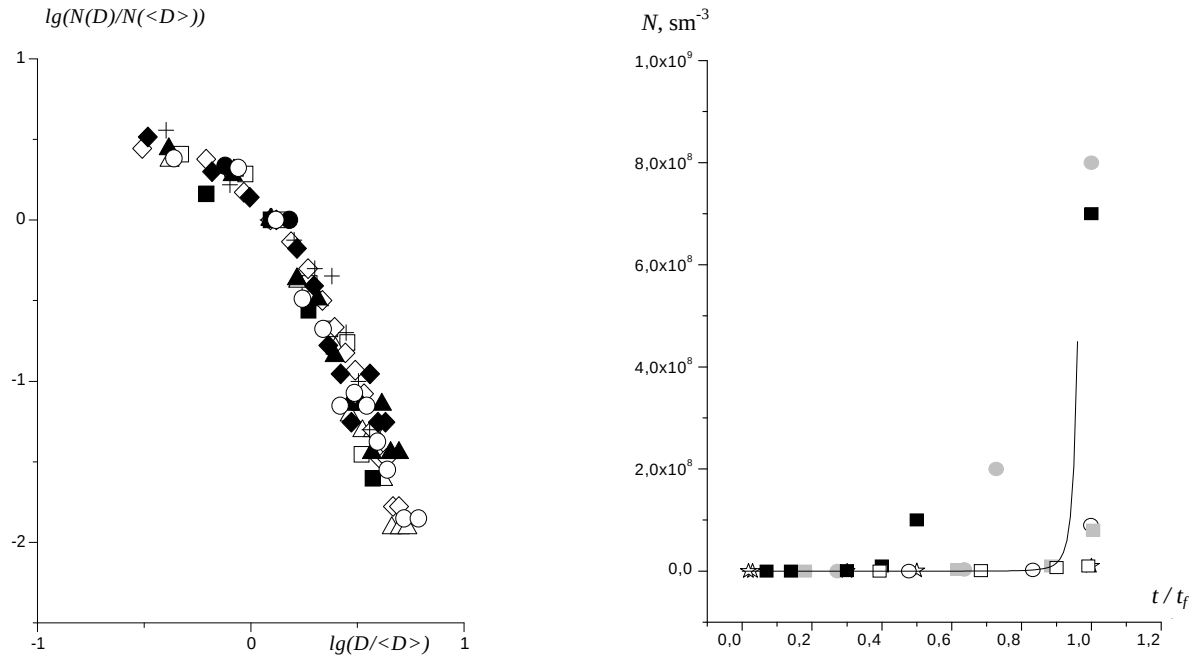

Figure 1. Size distribution of fracture centers in *Fe* (Δ=4·10^{-4}m thickness, dark markers) and *Cu* (Δ=10^{-3}m) samples in the sections parallel to the damaged surface (δ●(δ○)> δ■(δ□)> δ▲(δ△)> δ♦(δ◊)> δ+, where δ is the depth from the damaged surface (a) and the fracture centers accumulation rate (calculations and experiments) for various metals on the fracture time scale t_f (b).
-Pbσ$_1$, Δ=3·10^{-4}m; □- Pbσ$_2$, Δ=4·10^{-4}m; ◯ - Cuσ$_1$, Δ=2·10^{-4}m; ○ - Cuσ$_2$, Δ=4·10^{-4}m; ☆- Cu, Δ=5·10^{-5}m; ■ - Pb, Δ=2.3·10^{-4}m , σ$_1$>σ$_2$; ----- curve - solution of equation $dN/dt=N^{\beta}$, $\beta > 1$.

4. THE RESULTS OF FRACTOGRAPHIC STUDIES AND THE RESULT OF MATHEMATICAL SIMULATION OF THE VOLUMETRIC PERCOLATION CLUSTER OF FRACTURE CENTERS

The results of fractographic studies pointed to initiation of plastic flow areas (similar to turbulence – even at initial temperatures ($T \sim 4K$)) causing loss of the long-range lattice order near the forming and increasing fracture centers. These are deformation micro- and mesolevels (Fig.2).

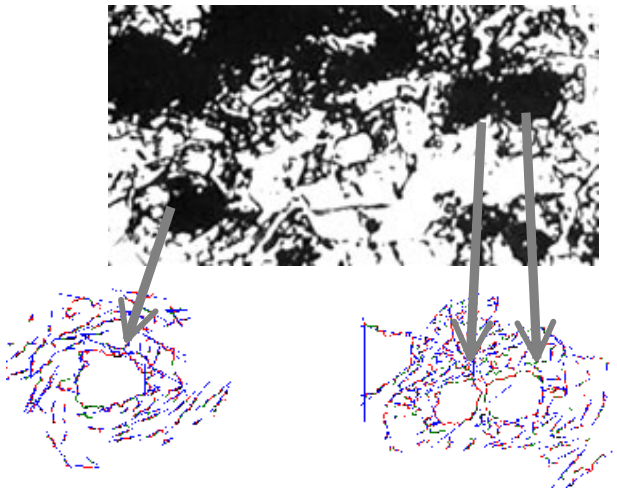

Figure 2. Structurization of the lattice slip bands near the growing fracture centers and tangents to the slip bands.

Fig.3 shows the result of mathematical simulation of the volumetric percolation cluster of fracture centers and the computer section produced by sectioning the volumetric percolation cluster with *Q* plane [2, 4]. Taking into account that there is an influence sphere around fracture centers having *R* size, which is connected with the plastic flow fields, and the fractographic analysis data, the following expression may be obtained

$$N^{-1/3} \cong 1.2R\,, \tag{1}$$

(*N* is the density of fracture centers). It allows transition from micro- to macrofracture to be estimated not only qualitatively, but also quantitatively (concentration criterion) [1].

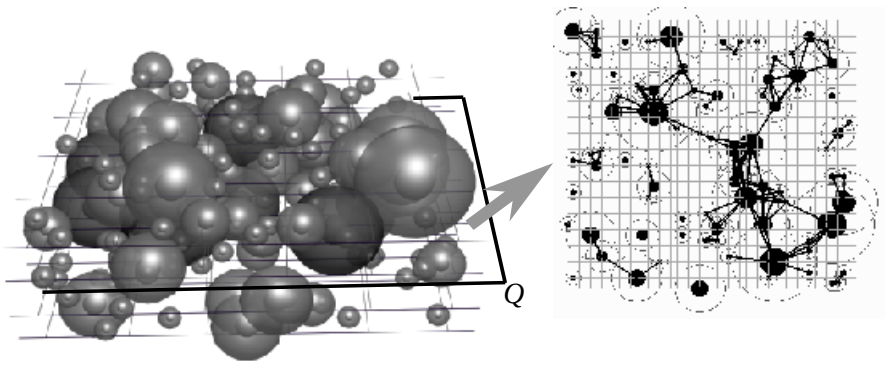

Figure 3. Percolation cluster of the fracture centers and percolation computer section produced by *Q* plane sectioning.

5. THE LONGEVITY DATA ON SOME METALS IN UNIVERSAL COORDINATES

Based on the structure-energy analogy of the metal behavior after introduction of thermal and mechanical energy, which in both cases results in the lattice long-range order violation, the longevity data on some metals are presented in universal coordinates (Fig.4). The universal coordinates make it possible to establish the time dependence of the relation between the critical density of the absorbed energy causing fracture and the lattice energy parameters (enthalpy - H and melting heat - L_m). The data in Fig.4 give the absolute values of dissipative unloading wave losses over the dynamic fracture range, they are close to a single curve and determine the boundary above which there is a fracture area. The insets in Fig. 4 show the change in the fracture mechanism from one-site to many-site. The systematized data over the quasi-static range are given for pure metals [5].

Taking into consideration the self-similar character of vulnerability to damage accumulation over the dynamic longevity range, the relation between the critical energy density and the longevity may be obtained: $E^{\gamma} \cdot t$ = const [1-3], where $\gamma \sim 3.8$. The derived expression determines the amplitude-and time coordinate irrespective of the loading method and geometry.

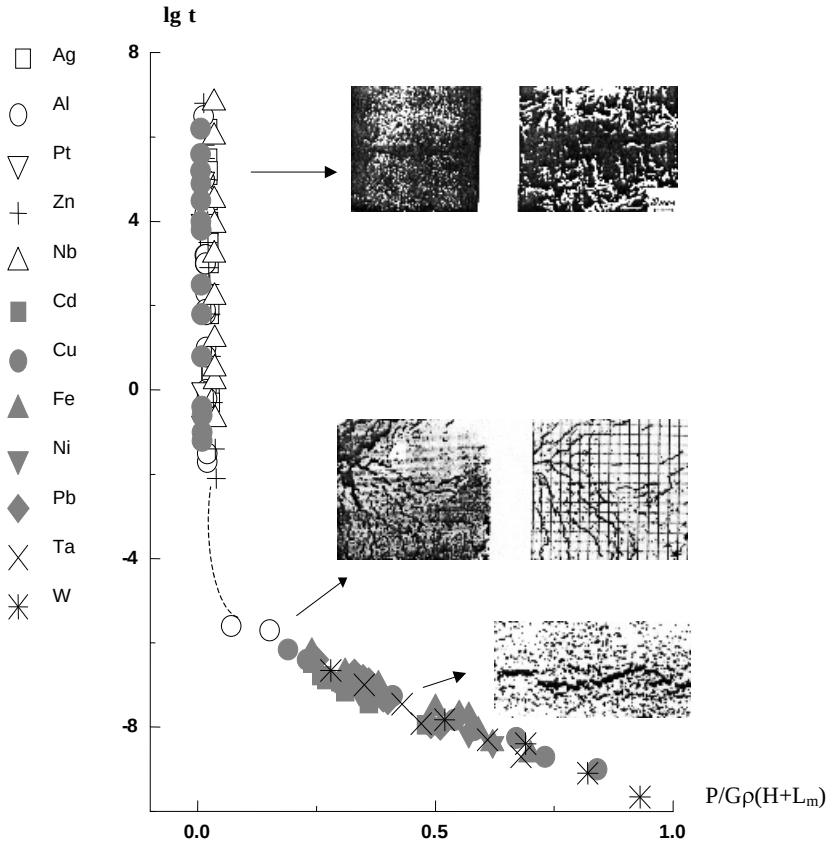

Table: $\rho(T,P)$, $H(T)$, $G(T,P)$, L_m
Measured: $E=P/G\rho$,
L_m – melting heat, H- enthalpy, G- Gruneisen parameter, ρ- material density

Figure 4. Dependences of *t* longevity for some metals in universal coordinates (*t* is in seconds).

6. CONCLUSIONS

The data given in Fig. 4, show the periodic dependence of the dynamic durability on *z*, that allows "to design" stable materials for the certain operating conditions by computer way (for example to choose the material for the output window screen of the pulse accelerator of the relativistic electrons etc.) [2, 3].

Thus, it is shown, that in the dynamic range of durability the thermodynamic potential enthalpy is the parameter which controls the process of dynamic destruction. The ratio of the density of the absorbed energy to the power parameters of the crystal lattice (of the enthalpy and the change of phase heat) is the invariant of the metals' behavior in relation to the external influences [2, 3].

At the amplitudes of the pulse pressure $P \sim 1 \div 30$ GPa, in the range of durability $t \sim 10^{-6} \div 10^{-10}$ s the evolution of the micro and mesoscopic defects in the phenomenon of the dynamic destruction is defining in the invariant metals' behavior under the influence of thermal shock [2, 3].

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