MECHANISMS AND CHARACTERISTICS OF DAMAGE AND FAILURE IN TERMS OF THE THEORY OF PHASE TRANSITION

L.R.Botvina*

New approach based on the phase transition theory is suggested for the analysis of the mechanical behaviour of materials allowing to estimate the order parameters and critical exponents in power-law relations describing a number of deformation and fracture processes. It is shown that this approach may be also used for the analysis of physical properties change during fracture processes. The kinetic diagram of internal friction is plotted which is similar by its shape to that of fatigue fracture and may be used for non-destructive testing of materials under cyclic loading.

INTRODUCTION

The possibility to consider fracture processes in terms of the phase transition theory is caused by the fact that fracture kinetic curves under different loading conditions are close by their shape to the isotherms of the liquid-vapor phase transition plotted in pressure vs density coordinates. By analogy to the liquid-vapor phase transition (Stanley (1)), the closeness to the critical point of the fracture process is defined by the order parameter which is a power-law function of the characteristics governing the loading conditions. An estimation of critical exponents in these power-law relations makes it possible to predict the reaching critical state of material under loading, accompaning by fracture mechanism change.

The purpose of this paper was to show that this approach allows to analyse the variations of both mechanical and physical properties reflecting damage accumulation under loading.

*A.A.Baikov Institute of Metallurgy, Russian Academy of Science, Leninskii prospekt, 117911 Moscow, Russia.

In Fig.1 we present schematically typical fracture kinetic curves $K=f(\tau)$ obtained under a constant value of the parameter P defining the test conditions (temperature,loading rate, size of structural elements, etc.; K is a certain strain and /or fracture property; τ is the time). It is clear that these curves remain similar to each other until a certain critical value of the parameter P is reached. For $P=P_C$, the second steady-state stage disappears on the fracture curves and they become closer to straight lines, as do the isoterms when the the critical temperature is achieved under the liquid-gas transition conditions (Botvina (2,3)).

Such a transition during failure is accompanied by the fracture mechanism change. According to the Frenkel's idea(4) any solid upon its loading may be considered as a two-phase material consisting of proper atoms and vacancies which are "atoms" of the second substance (voids). If the material is a two-phase one at the steady-state stage of fracture (i.e. consisting of damaged and undamaged volumes), we can assume that upon achievement of the critical conditions, a "phase transition" occurs with formation of a new phase: a macrocrack.

The length of the steady-state stage on the damage and fracture curves has been used as an order parameter for fracture process of a solid. This allowed to establish the new power-law relations and estimate the critical exponents characterizing the kinetics of pores formation during phase transition occuring in different loading conditions.

FATIGUE AND CREEP

As the order parameters of fatigue and creep fracture, the lifetime of the second stage (N, τ) of these processes developing under different stresses was used and the following relations was obtained:

$$(N - N_C)/N_C = A\,[(\sigma - \sigma_C)/\sigma_C]^{\beta} \quad \ldots\ldots\ldots \quad (1)$$

$$(\tau - \tau_C)/\tau_C = B\,[(\sigma - \sigma_C)/\sigma_C]^{\gamma} \quad \ldots\ldots\ldots \quad (2)$$

where N_C and τ_C the critical values of these order parameters at critical stress (σ_C) corresponding to disappearance of the steady -state stage on fracture curves. The exponents in these equations changed from 1.9 to 7 depending on material tested and loading conditions. In both cases the achievement of critical point has led to the change of fracture mechanism. At the cyclic loading the fracture mode changes from the normal rupture under low stress amplitudes to slantwise shear mode under high stresses. In creep conditions intercrystalline fracture at low stresses was replaced by transcrystalline one.

Similar analysis was fulfilled for processes of tension and impact loading (2,3).

In the case of the ductile-brittle transition at temperature decrease, the dependences of crack length on the time or the number of cycles are also similar to the curves presented in Fig.1 and become close to linear in the brittle fracture region under the critical temperature. It means that the linear mechanics fracture characteristics may be used only at and above the critical point.

The rate of reaching brittle state may be estimated by the exponent in the power law relation, connecting the order parameter of the process of the brittle-ductile transition (i.e. the lifetime corresponding to the stable stage of crack growth) with the test temperature.

INTERNAL FRICTION

It is known that structural changes in material during cyclic loading lead to the changing of its physical properties. From Fig.2, it can be seen that the internal friction of low carbon steel (Karius et al (5)) increases and the elasticity modulus decreases with increasing the number of cycles and the stress range. The family of the internal friction curves is a mirror reflection of the elasticity modulus ones (Fig.3) for this steel. It means that the observed relationships are related to the same structural changes occuring during cyclic loading. At the first, second and third stages which can be isolated on curves of Fig.2 and 3, the physical properties changes are connected respectively to increasing in dislocation density, accumulation of microcracks and to beginning of defects coalescence until the main crack forms. Thus,these structural changes confirm the general damage accumulation picture during fracture presented in Fig.1.

The second stage on the internal friction curves (Fig.2) disappears at the stress range equal to 320 MPa. Hence, the critical point of the phase transition corresponds to the stress 280 $<\sigma>$ 320 MPa. It is confirmed by the elasticity modulus curves (Fig.3), shape of which abruptly changes under the stress amplitude equal to 300 MPa.

In estimating the order parameter of this phase transition (N) and its normalized value,the power-law relation similar to the equation (1) has been established. It is presented by Curve *2* in Fig.4 where the dependence of the internal friction on the order parameter is also shown. The internal friction values correspond to those in the transition point from the second stage to the third one at the beginning of the main crack formation.

KINETIC DIAGRAM OF INTERNAL FRICTION

The dependences of the internal friction on the number of cycles (Fig.2) are similar by their shape to the fatigue crack growth curves, which are used for the plotting the kinetic diagram of fatigue fracture. Such a dependence for the internal friction is presented in Fig.5. It can be seen that all points in Fig.2 corresponding to the various stress ranges are situated on the unique diagram which may be described in its intermediate part by a power-law relation:

$$d\delta / dN = A(\sigma\sqrt{\delta})^n = AF^n$$

Similar to kinetic diagrams of fatigue fracture, this diagram has three parts limited by the threshold (F_{th}), transition (F_T) and critical (F_C) values of the governing parameter. These characteristics may be used for the non-destructive prediction of the material behaviour under loading.

REFERENCES

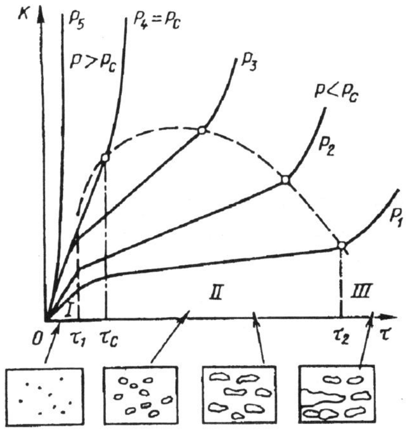
(1) Stanley, H.E.,"Introduction to Phase Transitions and Critical Phenomena" (Russian Translation), Mir, Moscow, 1973.

(2) Botvina, L.R., Metal Science and Heat Treatment, Vol.36., 1994, pp.393- 403.

(3) Botvina L,R., Proceeding of IUTAM Symposium, Cambridge University, 3-7 September, 1995, UK, (in press).

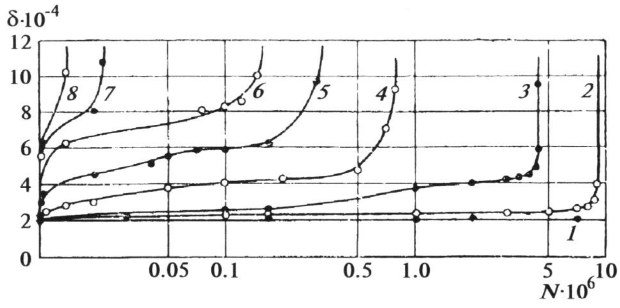
(4) Frenkel,J., "Statistical Physics", Izd.Akad.Nauk SSSR, Moscow Leningrad, 1948.

(5) Karius,A., Gerold ,E. and Shulz,E.H., Arch. Eisenhutten-wesen, H.5/6, 1944, pp.113-124.



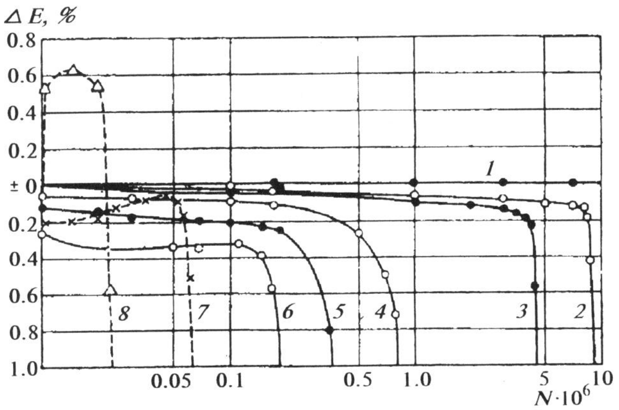
P - parameter governing the loading conditions
I,II,III - stages of damage accumulation

Figure 1 Typical time dependences of a characteristics (*K*) of deformation and/or fracture



stress amplitude σ(MPa):
1 - 210; *2* - 220; *3* - 230; *4* - 250; *5* - 260; *6* - 280; *7* - 320; *8* - 340.

Figure 2 Dependences of the internal friction (δ) on the number of loading cycles (*N*) for low carbon steel (*5*)



stress amplitude σ(MPa):
1 - 210; *2* - 220; *3* - 230; *4* - 250; *5* - 260; *6* - 280; *7* - 300; *8* - 320.

Figure 3 Dependences of the change of elasticity modulus (ΔE) on the number of loading cycles (N) for low carbon steel (*5*)

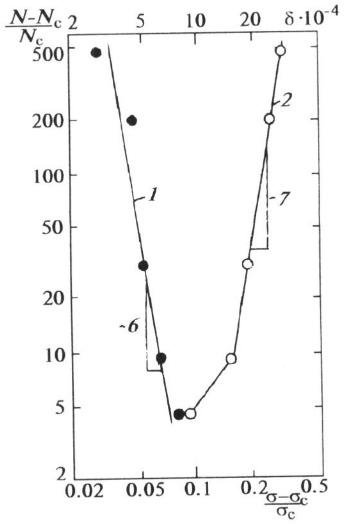


Figure 4 Dependences of δ (*1*) and $(\sigma\text{-}\sigma_C)/\sigma_C$ (*2*) on the order parameter

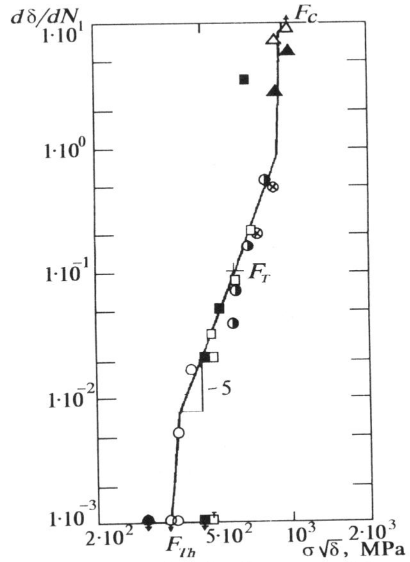


Figure 5 Kinetic diagram of the internal friction