Anomalous Behavior of Strength and Yield Limits under Short Pulse Loading. Possible Explanation of Embrittlement of Nuclear Constructional Materials Irradiated at Elevated Temperatures

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Principal features of the behavior of materials subjected to short pulsed loads are common for a number of seemingly different physical processes including such as dynamic fracture, yielding, cavitation, etc. In this paper examples illustrating typical dynamic effects inherent in these processes are analyzed. A unified approach to fracture and yielding in solids is proposed. Examples of different physical processes considered in the presentation show the fundamental importance of investigating the incubation processes preparing abrupt structural changes in continua under intense pulsed impacts. As an application of this approach some of the effects of anomalous behavior of yielding in materials subjected to intense short pulsed impacts (collisions with elementary particles) under elevated temperatures will be discussed. It will be shown that for high rate loaded material, increase of a sample temperature results in increase of critical yielding stress. This can result in brittle micro-cracking and damage of heated material irradiated by high energy particles.

1. INTRODUCTION

Experiments on the dynamic loading of solids reveal a number of effects indicating a fundamental difference between the fast dynamic rupture (breakdown) of materials and a similar process under slow quasistatic loads. For example, one of the basic problems in testing of dynamic strength properties of materials is associated with the dependence of the limiting rupture characteristics on the duration, amplitude, and growth rate of an external load, as well as on a number of other factors. While a critical value for strength parameter is a constant for a material in the static case, experimentally determined critical characteristics in dynamics are found to be strongly unstable, having a behavior that is unpredictable. The indicated (and some other) features of the behavior of materials subjected to pulsed loads are common for a number of seemingly quite different physical processes, such as dynamic fracture (crack initiation, propagation, arrest and spalling), cavitation in liquids, electrical breakdown in insulators, initiation of detonation in gaseous media, etc. Unified interpretation for fracture of solids, yielding and phase transforms is proposed, constituting structural-time approach [1-4], based on the concept of the incubation time of a transient dynamic process.

2. INCUBATION TIME CRITERION

The main difficulties in modeling the aforementioned effects of mechanical strength, yielding and phase transitions is the absence of an adequate limiting condition that determines the possibility of rupture, yield or phase transform. The problem can be solved by using both the structural fracture macromechanics and the concept of the incubation time of the corresponding process, representing nature of kinetic processes underlying formation of macroscopic breaks, yield flow or phase transformation. The above effects become essential for impacts with periods comparable to the scale determined by the fracture incubation time that is associated with preparatory relaxation processes accompanying development of micro defects in the material structure.

The criterion of fracture based of a concept of incubation time proposed in ([1-4] makes it possible to predict unstable behavior of dynamic-strength characteristics. These effects are observed in experiments on the dynamic fracture of solids. The fracture criterion can be generalized:

$$\frac{1}{t}\cdot\int_{t-t}^{t}\left(\frac{F(t')}{F_c}\right)^{a}dt' \le 1 . \qquad (1)$$

Here, $F(t)$ is the intensity of a local force field causing the fracture of the medium, F_c is the static limit of the local force field, and t is the incubation time associated with the dynamics of a relaxation process preparing the break. The fracture time t_* is defined as the time at which condition Eq. (1) becomes an equality. The parameter a characterizes the sensitivity of a material to the intensity of the force field causing fracture.

Using an example of mechanical break of a material, one of the possible methods of interpreting and determining the parameter t is proposed. It is assumed that a standard sample made of a material in question is subjected to tension and is broken into two parts under a stress P arising at a certain time $t = 0$: $F(t) = PH(t)$, where $H(t)$ is the Heaviside step function. In the case of quasi-brittle fracture, the material should unload, and the local stress at the break point should decreases rapidly (but not instantaneously) from P to 0. In this case, the corresponding unloading wave is generated, propagates over the sample, and can be detected by well-known (e.g., interferometric) methods. The stress variation at the break point can be conditionally represented by the dependence $s(t) = P - Pf(t)$, where $f(t)$ varies from 0 to 1 within a certain time interval T. The case $f(t) = H(t)$ corresponds to the classical theory of strength. In other words, according to the classical approach, break occurs instantaneously ($T = 0$). In practice, the break of a material (sample) is a process in time, and the function $f(t)$ describes the *micro- scale level* kinetics of the transition from a conditionally defect-free state ($f(0) = 0$) to the completely broken state at the given point ($f(0) = 1$) that can be associated with the macro-fracture event (Fig. 1). On the other hand, applying fracture criterion (1) to *macro- scale level* situation ($F(t) = PH(t)$), the relation for time to fracture $t_* = T = t$ for $P = F_c$ is received.

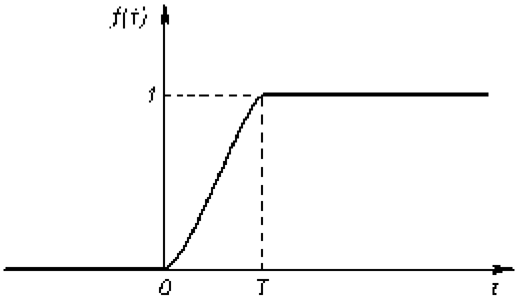

Fig. 1. Schematic representation of *micro- scale level* kinetics of fracture of a sample at the break point.

In other words, the incubation time introduced above is equal to the duration of the fracture process after the stress in the material has reached the static breaking strength *on the given scale level*. This duration can be measured experimentally statically fracturing samples and controlling the rupture process by different possible methods, e.g., measuring the time of the increase pressure at the unloading wave front, which can be determined by the interferometric (visar-based, or photoelasticity-based) method using the velocity profile of points of the sample boundary. Below, we analyze examples of the actual application of criterion Eq. (1) to various physicomechanical problems.

3. FRACTURE OF SOLIDS

Principal effects in the behavior of the dynamic fracture toughness [1] can be predicted and explained on the basis of incubation time notion. Rate dependences K_{Id} of the dynamic fracture toughness, which were observed in experiments, are characterized by a strong instability and can noticeably change when varying the duration of the load rise stage, the shape of the time profile of a loading pulse, sample geometry, and the method of load application (Ravi-Chandar and Knauss [5], Kalthoff [6], Dally and Barker [7]). The calculations based on the concept of the incubation time corresponding to the conditions of a number of experiments were carried out by Petrov and Morozov [1,2]. The total rate dependence of fracture toughness can be obtained on the basis of incubation time criterion Eq. (1). For the crack initiation problem under symmetrical loading conditions (K_I -mode) this criterion takes the form:

$$\frac{1}{t}\int_{t-t}^{t} K_I(t')\,dt' \le K_{Ic} \qquad (2)$$

where $K_I(t)$ is the time dependence of stress intensity at the crack tip. The scheme for the application of criterion Eq. (2) to crack growth initiation problems is given in[1-3].

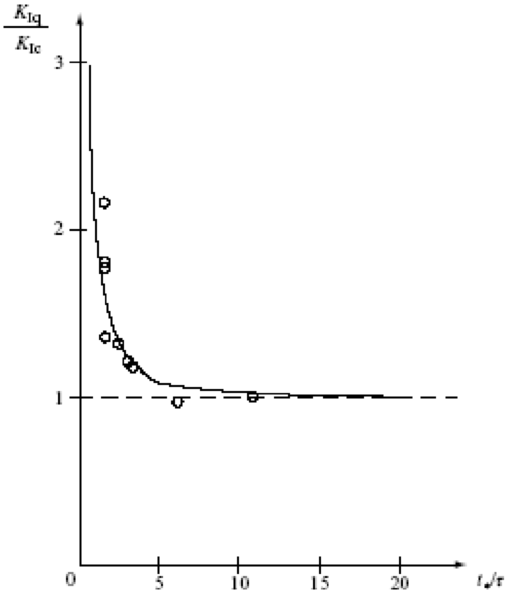

Fig. 2. Critical stress intensity factor versus time to fracture for Homalite-100. Calculation by incubation time criterion criterion Eq. 2 and experimental points by Ravi-Chandar and Knauss (1984).

An example of our *analytical* calculation using criterion Eq. (2) for the rate dependence of fracture toughness for Homalite-100 ($t = 9m\,s, K_{Ic} = 0.48 MPa\sqrt{m}$) for endless trapezoidal pulses of loading pressure applied to the crack faces is represented in Fig. 2 by the solid curve. Experimental points in Fig 2 were reported by Ravi-Chandar and Knauss [5].

On the other hand a decreasing and non monotonic behavior of dynamic fracture toughness with the decrease of time to fracture is also observed in a number of experiments (e.g. Kalthoff [6]. This phenomenon also can be predicted and explained by means of criterion Eq. (2) (Petrov and Morozov [1]). All manners of dynamic fracture toughness behavior – decrease, increase, and non monotonic change can be realized for any particular material with the same fixed material constants t and K_{Ic}.

Thus, our results show that the dynamic fracture toughness is not an intrinsic characteristic of a material. Moreover, the employment of both the criterion of the critical intensity factor $K_I(t) \le K_{Id}$ and the characteristic K_{Id} as a *material parameter* defining the dynamic strength (in analogy to the static parameter K_{Ic}) are incorrect.

4. DYNAMIC YIELDING

To explain a number of effects (e.g., the temperature dependence of the dynamic yield limit) and to determine the applicability limits for existing simple phenomenological models of yielding, it is necessary to develop a unified criterion for the yield, which is applicable in both the quasistatic and dynamic ranges of the strain rate. On the basis of the analysis of various generalizations of the classical yield limit criterion $\sigma(t) \le \sigma_y$ to the case of arbitrary load duration, the following relationship for determining the point in time corresponding to the onset of yield was suggested [8]:

$$\frac{1}{t} \cdot \int_{t-\tau}^{t} \left(\frac{\sigma(t')}{\sigma_y} \right)^{\alpha} dt' \le 1 \qquad (3)$$

Here, s_y is the static yield limit, α and τ are constants dependent on a material under consideration. It is assumed that the time is counted from the moment of stress application (i.e., $\sigma(t) = 0$ for $t < 0$). The yielding event is associated with equality in Eq. (3). It is natural to assume that τ is inversely proportional to the speed of dislocation motion. It is supposed that the speed of motion of dislocations can be defined by the relation suggested by Gilman, i.e.:

$$v = v_0 e^{-\frac{\Delta G}{kT}} ,$$

where ΔG is the free energy of activation, k is the Bolzman constant. From this relation, the relationship for the yielding incubation time can be obtained:

$$\tau = \tau_0 e^{\frac{\Delta G}{kT}} ,$$

where τ_0 can be associated with the characteristic time for dislocation movement along the material structural size (i.e. mean grain size). The temperature dependence of parameter α is defined by the expression $\alpha = c_1 + c_2 / T$, where c_1, c_2 are material constants. In the above relationships T is the absolute temperature.

To study temperature dependences of α and τ , criterion Eq. (3) was utilized to describe the experimental data of Campbell and Ferguson (Campbell and Ferguson [8]**)** studying the yield limit of mild steel for strain rates (de/dt) in a wide range ($10^{-3} \div 10^{5} s^{-1}$) for a wide range of temperatures. By an appropriate choice of the constants c_1, c_2 calculated curves were fitted (see Fig. 3) to the reported experimental data for each of the six temperatures (from 195 to 713 K).

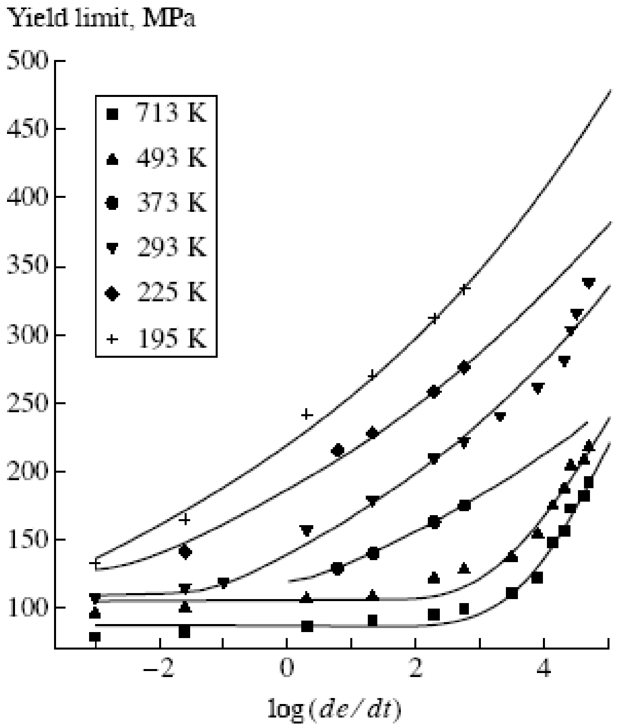

Fig. 3. Calculated on the basis of Eq. (3) and experimental (Campbell and Ferguson [8]) dependences of the dynamic yield limit on the strain rate for a mild steel at various temperatures.

The fact that the incubation period varies means that the strain-rate range where the dynamic properties affect the situation shifted. The strain rate is affecting material at low temperatures as being higher than the same rate at room or elevated temperatures. This corresponds to the well known hypothesis that a decrease in temperature is equivalent to an increase in the strain rate. Criterion Eq. (3) allows quantitative estimations of this effect.

5. TEMPERATURE ANOMALY OF YIELD STRESS BEHAVIOUR UNDER PULSED LOAD

Another example of the anomalous behavior of materials under high-speed loading is the increase in the dynamic yield stress of the material upon an increase of temperature described in [9]. It was found that for strain rates in the rage of order of 5x10^{5} s^{-1}, the yield stress of highly pure titanium increases with the temperature of the material. An analogous effect was observed for monocrystalline aluminum. In these experiments, the samples were subjected to the impact, leading to the emergence of plane compression waves in the material. The pulse amplitude for titanium was 4.5–6.5 GPa, and the temperature of the samples was varied from room temperature to 405–460°C. The yield stresses in monocrystalline aluminum were measured in the temperature range from 15 to 650°C, and the pulse amplitude was 5 GPa.

Using incubation time criterion it can be shown that at elevated temperatures for high loading rates increase in temperature results in increase of the yielding stress [10]. Fig. 4 illustrates this phenomenon. This effect becomes very important for materials inside atomic reactors being subjected to highly intense and short impacts from high energy particles colliding with material.

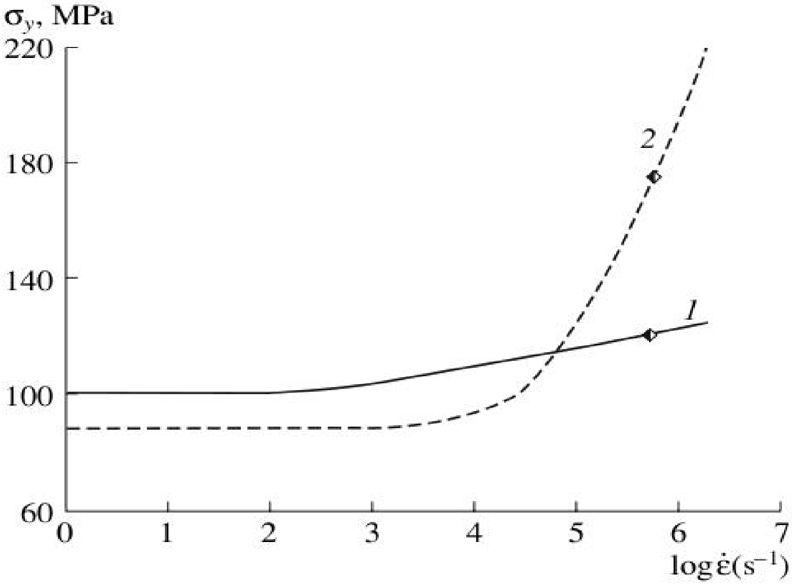

Fig. 4. Dependence of the dynamic yield stress for highly pure titanium on the strain rate. Symbols correspond to experimental data by G. Kanel, and curves 1 and 2 are calculated using criterion Eq. (3) for T = 293 and 738 K, respectively.

Thus, in accordance with the proposed model, the effect of an anomalous increase in the yield stress upon an increase in temperature can be explained by the competition between the rate sensitivity of the material (determined by parameter τ) and its sensitivity to the loading level (determined by parameter α). It should be noted that this yield criterion makes it possible to describe the behavior of the material in the entire range of strain rates. At low strain rates, it is transformed into its static analog. At high strain rates, this criterion may form the basis for deriving an analytic expression for strain-rate dependences of the yield stress at various temperatures. In this case, the temperature– time conformity principle typical of moderate strain-rate modes is fulfilled. According to this principle, the increase in the yield stress is observed during cooling of the material as well as upon an increase in its strain rate. On the basis of the phenomenological model of yield proposed in this study, qualitative comparison with the available experimental results is carried out. To establish a more accurate quantitative correspondence, further experiments are required, including measurement of the yield stress at fixed temperatures and various strain rates.

6. EMBRITTLEMENT OF NUCLEAR CONSTRUCTIONAL MATERIALS IRRADIATED AT ELEVATED TEMPERATURES

Described above fracture model is used to assess possibility that impacts of high energy particles can create microscopic rupture at material used inside nuclear reactors. As shown earlier, at elevated temperatures (and to such conditions constructions inside nuclear reactors are usually subjected) ductile-to-brittle transition of fracture under high rate dynamic loads mechanism can take place. Here the preliminary and maybe rather oversimplified estimations of possibility, that high energy particles being captured by bulk material inside reactor can cause formation of microdefects of brittle nature are made.

Criterion (2) is used to assess conditions resulting in formation of brittle rupture. To use (2) one needs to be aware of critical tensile stress σ_c , that material can withstand under quasistatic loading conditions and incubation time of fracture t . As fracture that is going to be analyzed is happening on level close to atomic, the choice of fracture parameters should be appropriate. Ultimate stress σ_c can be taken to be equal to theoretical strength of material, calculated from the first principles for an ideal crystal. Incubation time of a fracture process τ in this case can be taken too be equal to the time longitudinal wave needs to travel a distance equal to inter atomic distance. For iron value for theoretical critical tensile stress was calculated for example by Friak et al. [11] and is equal to 27.3GPa. Interatomic distance for crystalline Fe is 2.6 Å. Speed of a longitudinal wave is 5120 m/s.

To simplify the problem finite Heaviside step function impact is supposed. It is supposed that in a half plane $x_2<0$ compression wave with a front parallel to the border was created:

$$\sigma_{22} = -P\left(H\left(t - \frac{x_2}{c_1} \right) - H\left(t - \frac{x_2}{c_1} - T \right) \right), \text{ for } t<0.$$

Being reflected from the boundary $x_2=0$ the wave is changed to tensional and can produce rupture. Specific (per unit of length) energy, needed to create such a wave can be easily calculated in [12] and is equal to:

$$E_{spec} = \frac{P^2 T}{c\,\rho} \ ,$$

where c is the longitudinal wave speed and ρ is mass density. Density of crystalline iron is 7860 kg/m^3. Minimal energy being able to create rupture is reached for pulse of amplitude $P=\sigma_c$ and duration $T=\tau$.

Thus we can calculate energy per interatomic distance, that is needed to produce microcrack. This energy will be $E=\frac{P^2 d^2}{c^2 \rho}$, where *d* is interatomic distance. For crystalline iron energy per interatomic distance needed to produce microcrack with size of *d* is found to be approximately 2.5 10-10 Joules or 1.5 GeV.

This result is considered to be rather promising. 1.5 GeV is about the upper limit for energies of particles that are radiated in atomic reactors. Thus, probability that such an energy will be transmitted to irradiated material in a point of interest during a time comparable to τ is not very high (otherwise this would mean that bulk material should be completely distorted after not very long time inside reactor) and is not vanishingly small. The result indicates that it is possible that small brittle cracks sized several interatomic distances can be created in a result of radiation with high energy particles inside atomic reactors. This process can be assisted by hydrogen embrittlement of material due to hydrides are build on grain boundaries [13]. This can result in decay of critical tensile stress, making rupture possible even at lower energies. Also it is possible, that voids created due to high energy particles colliding with bulk material can absorb gaseous hydrogen. This can result in creation of internal stresses inside material and, hence, make fracturing easier. We understand that estimations presented are very oversimplified. Nevertheless this estimations show that at lest order of magnitude of energy required to produce microscopic fracture is reasonable and proposed mechanism can coexist together with other embrittlement mechanisms and can compete with them or assist them.

7. CONCLUSIONS

Thus, the examples of different physical processes considered above show the fundamental importance of investigating incubation processes preparing abrupt structural changes (fracture and yielding) in continua under intense pulsed loads. The fracture incubation time is evidently a universal basic characteristic of the dynamic strength and must become one of the main material parameters to be experimentally determined (measured). The above results show that the incubation-time approach is fundamental and makes it possible to adequately represent the dynamics of fracture, yielding as well as other structural transforms. It was shown that it is possible that high energy particles colliding with bulk material at elevated temperatures can cause damage (i.e. micro-cracking).

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