01.5;06.4

Micro-mechanismof multiscale dynamic fracture

© Yu.I. Meshcheryakov[1], A.K. Divakov[1], N.I. Zhigacheva[1], G.V. Konovalov[1], A.F. Nechunaev[2]

[1] Institute of Problems of Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, Russia
[2] St. Petersburg State University, St. Petersburg, Russia
E-mail: ym38@mail.ru

Received February 14, 2022
Revised March 22, 2022
Accepted April 4, 2022

The shock propagation in non-uniform medium is studied theoretically and experimentally. A set of experiments on shock loading of high-strength low-alloyed AB2 steel is performed. The „trigger" mechanism for switching the dynamic fracture from one scale to another is shown to be the resonance interaction of plastic flow oscillations and mesoscopic structural elements. There is a threshold strain rate at which the defect (decrease) of mass velocity at the plateau of compressive pulse increases abruptly. Under strain rates higher threshold value, a multitude of short transcrystalline cracks is formed, which results in decay of shock wave.

Keywords: Shock loading, multiscale fracture, transcrystalline cracks.

DOI: 10.21883/TPL.2022.05.53483.19163

The purpose of this paper is to elucidate a question related to the physics of multiscale dynamic deformation, namely, to find out what is the nature of the „trigger" mechanism by which the dynamic deformation process and fracture micro-mechanism switch from one scale level to another. To answer this question, the problem of shock wave propagation in a structurally heterogeneous medium has been considered, and a series of experiments on shock loading of steel AB2 has been conducted.

Shockwave experiments and theoretical analysis of the shockwave behavior of a structurally non-homogeneous environment have revealed the following correlation between the variation of the mass velocity of the dynamically deformed medium D (the square root of the velocity dispersion D^2 or standard velocity deviation) and the deformation rate $\frac{d\varepsilon}{dt}$ [1]:

$$D = R\frac{d\varepsilon}{dt}. \qquad (1)$$

A similar relation is known in the theory of turbulence, where the intensity of turbulent pulsations is proportional to the acceleration of the medium particles [2]. Another important characteristic of the shock-deformed medium is the so-called „velocity defect" Δu, which characterizes the change in mass velocity in the shock wave due to meso−macro energy exchange. In shock-deformed media, the dispersion and velocity defect are not independent quantities [3–5]:

$$\Delta u = -\left(1/2\right)\left(dD^2/du\right). \qquad (2)$$

In case of one-dimensional shock wave propagation, the momentum balance equation and the continuity equation for the normal components of stress σ, strain ε and mass velocity u are as follows:

$$\rho\frac{\partial u}{\partial t} - \frac{\partial \sigma}{\partial x} = 0, \quad \frac{\partial u}{\partial x} - \frac{\partial \varepsilon}{\partial t} = 0. \qquad (3)$$

The defining equation for closing the balance equations can be expressed in terms of plastic strain rate $\frac{\partial\varepsilon^p}{\partial t}$ in the following form [6]:

$$\frac{\partial\sigma}{\partial t} - \rho C_l^2\frac{\partial\varepsilon}{\partial t} = -2\mu\frac{\partial\varepsilon^p}{\partial t}, \qquad (4)$$

where C_l — longitudinal speed of sound, μ — shear modulus, ρ — material density. The plastic strain rate in this equation is expressed through the average density N_d and the average velocity V_d of mobile dislocations in the form of the Orovan equation

$$\frac{\partial\varepsilon^p}{\partial t} = bN_dV_d.$$

In this study, we assume that the relaxation of a dynamically deformed medium is due to the motion of elementary deformation carriers at the meso-level. This implies that, unlike [6], the plastic strain rate in expression (4) is determined by the rate of change of the mass rate defect

$$\frac{\partial\varepsilon^p}{\partial t} = \frac{1}{C_l}\frac{\partial\Delta u}{\partial t}. \qquad (5)$$

The advantage of this approach is that the relaxation model does not include dislocation structure parameters. In contrast to the parameters of the dislocation structure, the velocity defect is a measurable value in real time. The balance equations (3) can be reduced to the equation

$$\rho\frac{\partial^2\varepsilon}{\partial t^2} - \frac{\partial^2\sigma}{\partial x^2} = 0. \qquad (6)$$

Substituting relations (1) and (2) into (5), we obtain

$$\frac{\partial\varepsilon^p}{\partial t} = \frac{R^2}{C_l^2}\frac{\partial^2\varepsilon}{\partial t^2}. \qquad (7)$$

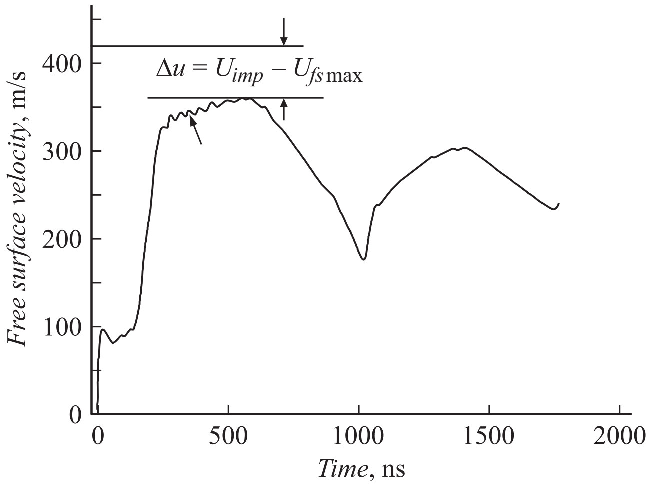

Figure 1. Temporal profile of the free surface velocity U_{fs} at the impactor velocity $U_{imp} = 423.9$ m/s.

Using (7), let us reduce equation (6) to the form

$$\frac{\partial^2 \varepsilon}{\partial t^2} - \rho C_l^2 \frac{\partial^2 \varepsilon}{\partial x^2} - 2\left(\mu R^2/\rho C_0^2\right)\frac{\partial^4 \varepsilon}{\partial x^2 \partial t^2} = 0. \quad (8)$$

In the case of stationary propagation of a plastic wave with velocity C_p, we can go to one variable $\xi = x - C_p t$:

$$\rho\left(C_p^2 - C_l^2\right)\frac{\partial^2 \varepsilon}{\partial \xi^2} - 2\mu \frac{R^2}{C_p^2}\frac{\partial^4 \varepsilon}{\partial \xi^4} = 0. \quad (9)$$

After replacing $\varepsilon_{\xi\xi} = \psi$, we get

$$\left(C_1^2 - C_p^2\right)\psi + 2\left(\mu R^2/\rho C_p^2\right)\frac{\partial^2 \psi}{\partial \xi^2} = 0. \quad (10)$$

This is the oscillator equation

$$\frac{\partial^2 \psi}{\partial \xi^2} + \frac{\rho C_p^2 (C_l^2 - C_p^2)}{2\mu R^2}\psi = 0. \quad (11)$$

From equation (11) it follows that the oscillation frequency is

$$\omega^2 = \frac{\rho C_p^2}{2\mu R^2}\left(C_l^2 - C_p^2\right). \quad (12)$$

As an example, Fig. 1 shows the time profile of the free surface velocity U_{fs}.. The profile shows an elastic precursor, a plastic front, and a plateau with oscillations (indicated by the arrow) and a velocity defect $\Delta u = U_{imp} - U_{fs\,max}$. For an impact with impactor velocity $U_{imp} = 423.9$ m/s, the spatial period of oscillation is $\sim 100\,\mu$m.

In the present paper, it is assumed that the trigger mechanism for switching the process of dynamic deformation from one scale level to another is the resonance interaction of meso-level structural elements with plastic flow oscillations. Resonance occurs when the spatial period of plastic flow oscillations coincides with the size of structural elements. To verify this assumption, an experimental study of the shock behavior of martensite-bainitic AB2 steel (hardness 235NV) was carried out in the impactor velocity range of 122–450 m/s. In each experiment, the time profile of the free surface velocity $U_{fs}(t)$ was recorded with a velocity interferometer. This technique makes it possible to record the difference between the impactor velocity and the maximum value of the free surface velocity, i.e. velocity defect. The free surface velocity at which the velocity defect begins to increase sharply determines the structural transition threshold. This changes two characteristics of the material response to impact loading: 1) magnitude of variation in mass velocity; 2) magnitude of the velocity defect and its dispersion by velocity. Figure 2 shows the dependences of velocity variation $D = f(U_{imp})$ and velocity defect $\Delta u = f(U_{imp})$ on impactor velocity. At a velocity speed of 371.1 m/s the course of the curves changes abruptly (line NN').

Microstructural studies were performed on the specimens in order to identify the fracture micro-mechanism. The specimens were cut along one of the planes along the impact direction, polished, etched in 5% nitric acid solution and then examined using microscope „Axio-Obsevier-Z1m“. At loading rates below the threshold velocity (in the range of 183–371. 1 m/s), localized deformation and cracking occur along crystallite boundaries of 5–20 μm, with micro-cracks often enveloping large-scale structures of 50–100 μm, consisting of smaller crystallites (Fig. 3, *a, b*). The resonant rocking of structural elements under the influence of plastic flow oscillations is a trigger process which initiates a change in the fracture micro-mechanism. This leads to the separation of conglomerates into small-scale crystallites (Fig. 3, *c*) and the formation of a series of short micro-cracks. Above the threshold velocity, trans-crystalline fracture occurs where micro-cracks of 5–20 μm cross the crystallite body. The micro-crack

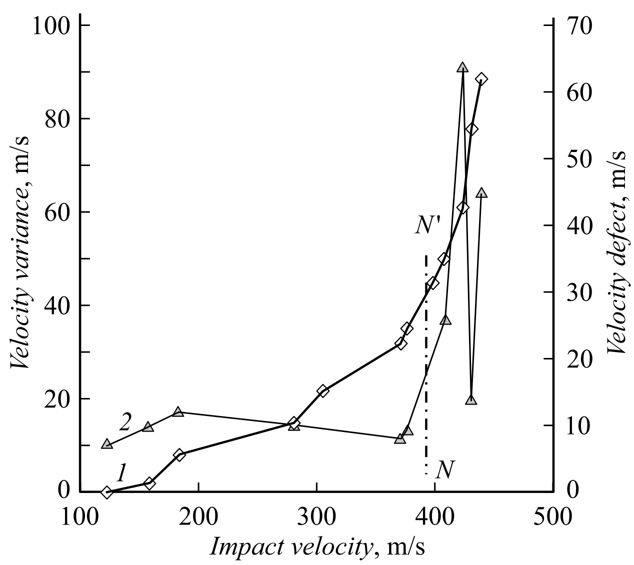

Figure 2. Dependences of the mass velocity variation D (*1*) and velocity defect Δu (*2*) on the impactor velocity U_{imp}.

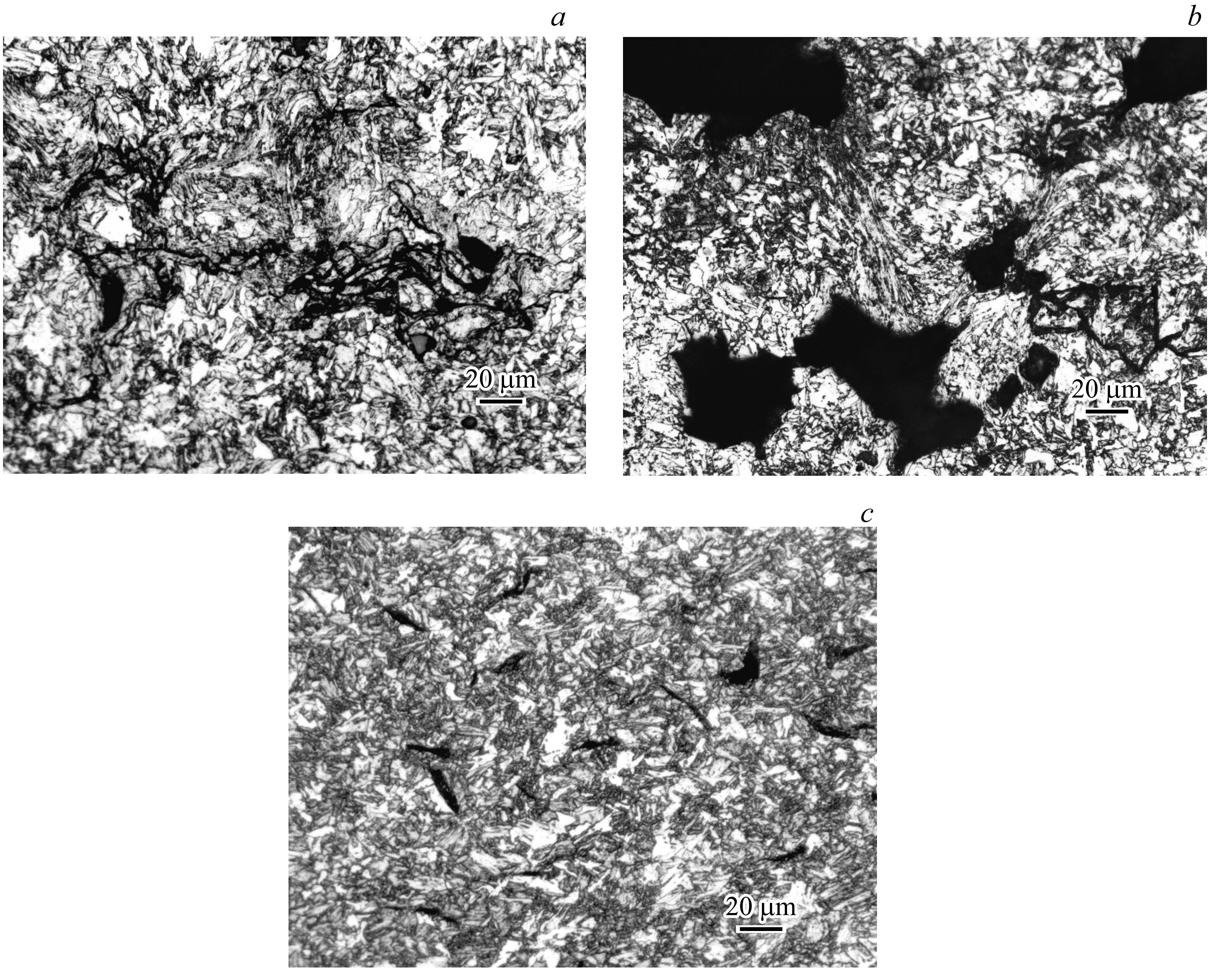

Figure 3. Fracture morphology of AB2 steel in the „pre-threshold" (a, b) and „above the threshold " (c) loading velocity regions.

density increases with the rate of impact loading. A sharp increase in the velocity defect is indicative of a strong damping of the shock wave at „above the threshold" velocities of dynamic deformation. In this connection, AB2-type steels can be used as highly absorbing layers in multilayer barriers designed to protect against shock loads [7].

Thus, the following conclusions can be made. A characteristic feature of the multi-scale dynamic fracture of AB2 steel is the presence of a threshold strain rate at which the velocity defect on the compression pulse plateau changes abruptly. At the threshold strain rate, the cracking character changes: grain boundary fracture is followed by transcrystalline fracture. The trigger mechanism for the switching of the dynamic fracture micro-mechanism is the resonance interaction of the structural elements with the oscillations of the plastic flow.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] D.A. Indeitzev, Yu.I. Meshcheryakov, A.Yu. Kuchmin, D.S. Vavilov, Acta Mech., **226** (3), 917 (2014). DOI: 10.1007/500707-014-1231-0
[2] J.O. Hinze, *Turbulence* (McGraw Hill, Inc., N.Y., 1962).
[3] Yu.I. Meshcheryakov, A.K. Divakov, N.I. Zhigacheva, I.P. Makarevich, K. Barakhtin, Phys. Rev. B, **78** (6), 064301 (2008). DOI: 10.1103/PhysRevB.78.064301
[4] Yu.I. Meshcheryakov, *Multiscale mechanics of shock wave processes* (Springer Nature, 2021).
[5] T.A. Khantuleva, Yu.I. Meshcheryakov, Phys. Mesomechanics, **19** (4), 3 (2016).
[6] J.W. Taylor, J. Appl. Phys., **36** (10), 3146 (1965). DOI: 10.1063/1.1702940
[7] H. Nahme, V. Hohler, A. Stilp, in *Shock compression of condensed matter-1991*, ed by S.C. Schmidt, R.D. Dick, J.W. Forbes, D.O. Tasker (Elsever Science Publ. B.V., 1992), p. 435.