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ON THE STRUCTURAL INSTABILITIES OF SHOCK LOADED MATERIALS

Yu.I. Meshcheryakov*, A.K. Divakov, N.I. Zhigacheva

Institute of the Problems of Mechanical Engineering, Bol'shoi pr. 61, Saint-Petersburg, 199178, Russia

*e-mail: ym38@mail.ru

Abstract. Experimental examples of shock-induced structural instabilities in solids, which are nucleated in the process of multiscale dynamic deformation, are considered from the position of methods of registration. The criterion for nucleation of instability, which includes the particle velocity variation at the mesoscale, supposes that instability arises when rate of change of the velocity variation within the shock front becomes higher than rate of change of the mean particle velocity.

Shock-induced structural instability of constructional materials has been the subject of investigations over the last fifty years to the present day. A critical issue in this field of study is that during the multiscale deformation the instabilities may be realized in the form of different deformation mechanisms depending on scale level. Such a variety of instabilities results from heterogeneous character of dynamic deformation. This supposes that beside the average particle velocity which reflects the macroscopic response of material on shock loading, there is particle velocity distribution. Similar scheme of a multiscale dynamic deformation is presented in Fig. 1. The dotted lines present the mean position of the front in a uniform medium, whereas the meandering lines are the random positions of separate pieces of the shock front. One can regard the motion of the shock front in a heterogeneous medium as a superposition of two modes of motion: a mean motion, which is approximately the motion of the plane front, and rapidly fluctuating motions resulting from the local stress fields.

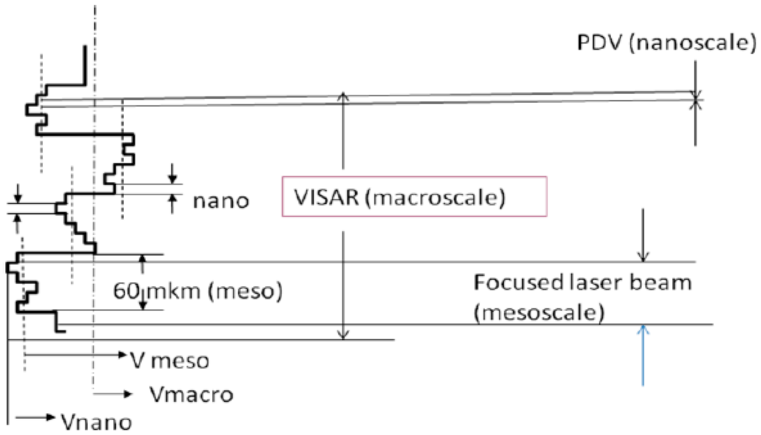
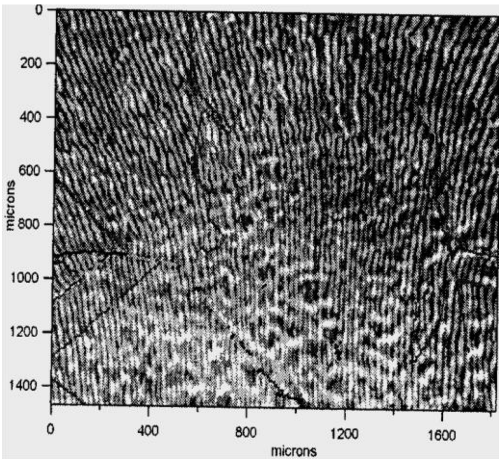


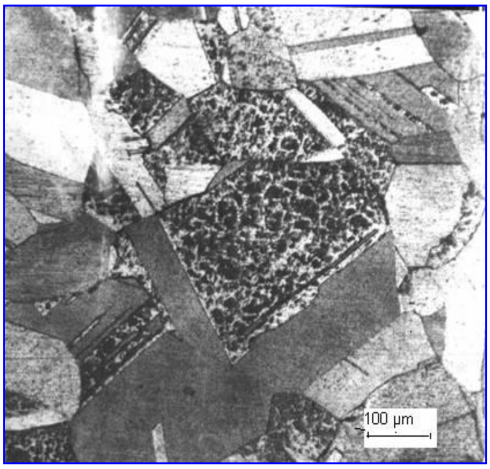
Fig. 1. Qualitative scheme of shock front in heterogeneous medium and measuring technique for different scales.

The shock front presents a complex hierarchic structure in the space-velocity coordinates. The separate pieces of shock front have the different velocities depending on the position and scale level. In this connection, experimental techniques for registering the response of material on shock loading are also organized in accordance with hierarchic scheme. To date, registration of mobility of structural elements at the highest scale level becomes possible by using the PDV (Photonic Doppler Velocity) interference technique, which provides the precise registration of instability sources at the nanoscale. These instabilities looks as microjets and can be considered as initial stage of the so-called Richtmayer-Meshkov instability [1]. One of example of shock-induced local instability corresponding to nanoscale fixed in our experiments is presented in Fig. 2. Inside the VT-14 titanium alloy target, after shock loading with the impact velocity of 565 m/s, a lot of snake-like structures have been found near the spall zone of target. These structures result from transition of the material into structure-unstable state within the local regions of target. They have been "frozen" due to instant removing the surround material in spall zone.

(a)



(b)



(c)

Fig. 2. "Frozen" structural instabilities in VT-14 titanium alloy target (a), turbulent structures at the free surface of target (*b*) and inside the grains in M3 and M2 copper (*c*).

The mesoscale instabilities have been fixed in shock-deformed copper in [3] and [4]. Using the high-velocity camera, the authors of [4] fixed the round 3D-structures at the free surface of target. The structures are indicated to be nucleated during the direct passage of shock front through the target. In [3] the analogous 3D-structures have been fixed inside the properly oriented grains in M3 and M2 copper, see Fig. 2(*c*).

In the case of dynamic strain, the real physical carriers of deformation at the mesoscale (point defects, dislocations, twins, planar defects) contributing to shock deformation cannot be identified. The only characteristic of structure which can be estimated by using interference techniques is the spatial scale of the correlated motion of elementary carriers of deformation (ECD). The regions of correlated motion of ECD play the role of mesoparticles. The scale of such a kind of mesoparticle d is estimated to lie within the interval $\lambda_0 << d << L$, where λ_0 is the wavelength of laser radiation and L is the diameter of the laser beam. For $\lambda_0 \approx 0.6$ μm and laser spot dimension of ≈ 60 μm, the mean size of the mesoparticles equals approximately 6 μm.

The correlated motion of ECD at the mesoscale appears as particle velocity pulsations. This motion is certainly a stochastic process that must generally be described using the language of the particle velocity distribution function (PVDF) and/or its statistical moments. Zero statistical moment is a density, the first moment is a mathematical expectation or mean particle velocity, and the second moment is a particle velocity dispersion:

$$\rho(r,t) = \int_{-\infty}^{\infty} f(x,v,t)dv, \tag{1}$$

$$u(x,t) = \frac{1}{\rho}\int_{-\infty}^{\infty} vf(x,v,t)dv, \tag{2}$$

$$D^2 = \int_{-\infty}^{\infty} (v-u)^2 f(x,v,t)dv, \tag{3}$$

The mobility of elementary carriers of deformation at the mesoscale and transition into structure-unstable state can be performed by using the Sandia velocity interferometer the laser beam of which is focused up to 50-60 μm [2, 3]. The spot of laser beam at the free surface of target just corresponds to one element of mesoscale (see Fig. 1). One mesoscale element, in turn, contains approximately hundred elements of nanoscale. The interference technique developed in [2] allow to record not only the free surface velocity profile – response of individual mesoscale element- but also the particle velocity variance for the nanoscale elements. In this case, the particle velocity variance is a quantitative characteristic of velocity distribution of nanoelements inside the one mesoselement. In accordance with the criterion obtained in [3], the structural instability at the mesoscale occurs when rate of change of the velocity variance is higher than the rate of change of the mean particle velocity for the separate structural element at the mesoscale:

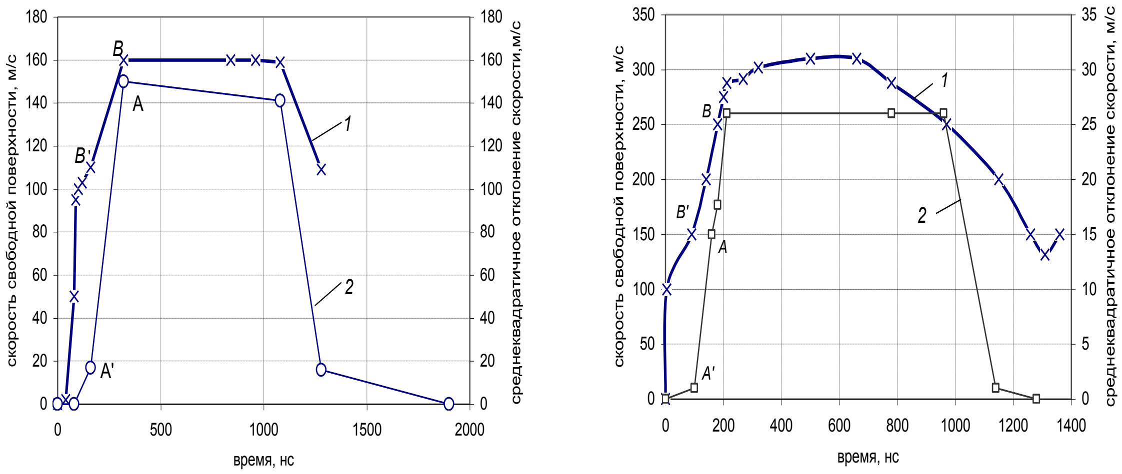
$$\left(\frac{D}{u}\frac{\dot{D}}{\dot{u}}\right) \geq 1. \tag{4}$$

In Figure 3 the mean velocity and velocity variance profiles are presented for two 5 mm steel targets shocked under approximately identical impact velocities of 320 m/s and 310 m/s. The targets have different initial structural state because of different histories of thermo-mechanical treatment. It follows from the experimental profiles that $\left(\frac{D}{u}\frac{\dot{D}}{\dot{u}}\right) = 0,71$ and $\left(\frac{D}{u}\frac{\dot{D}}{\dot{u}}\right) = 2,18$ for the first and second shocks, respectively. The transition into structure unstable state at the mesoscale occurs only for the first shock where the velocity defect at the plateau of compressive pulse achieves 150 m/s.

Conclusions

1. Macroscopic structural transition reveals in appearance of the velocity defect at the plateau of compressive pulse.

2. Momentum and energy exchange between scales is realized by means of coupling the particle velocity dispersion and velocity defect.
3. Structural transition at the mesoscale occurs when rate of change the particle velocity dispersion becomes higher than rate of change of mean particle velocity.



(a) *(b)*

Fig. 3. Free surface velocity profiles (1) and velocity variance profiles (2) for two 5 mm 30KHN4M steel targets loaded under impact velocity of 320 m/s (*a*) and 310 m/s (*b*).

References

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