ABOUT ROTATIONAL AND TRANSLATIONAL MODES OF PLASTICITY AND FRACTURE INITIATED BY DYNAMIC LOADING OF MATERIALS

Yu. I. Mescheryakov*, V.B. Vasilkov, S.A. Atroshenko
Institute of problems of mechanical engineering
Russian Sciences Academy
Russia, 199178, Sankt-Petersburg, VO, Bolshoi, 61

ABSTRACT

An approach based on the multiscale micromechanisms of dynamic deformation is developed. The coupling between kinetics of elementary carriers of deformation and macroscopic strength of materials is studied on example of three kind of ductile steel loaded within flyer velocities 100-500 m/s. Transition between mesoscopical (10^{-4} - 10^{-2} cm), superstructural (2-10 grain sizes), and macroscopical scale levels is found to take a translational or rotational form depending on the particle velocity distribution (PVDW) at the corresponding scale level. The main sense of that characteristic is reduced to ability of a material structure to rapid relaxation of internal stress at that level. The increasing of PVDW at the mesolevel leads to decreasing analogous value at the superstructural level, that is kinetic characteristics of adjacent scale levels are in opposite phase. The evidence is available that the greatest dynamic tensile and shear strength appears to be inherent to materials in which rotational mechanisms of deformation and fracture is realized, in distinction from materials with translational ones, where shear strength is the smallest.

INTRODUCTION

The well-known structural models of dynamic fracture have been grounded on the processes of nucleation, growth and the coalescing of the cracks and voids [1]. Similar approach can not be considered as universal because they take into account the dilatational part of tensile stress only. Indeed, for a number of materials dilatational part of stress is significantly higher than shear one. At the same time the processes of nucleation and growth of cracks and voids are thought the only channel of stress relaxation, especially if material has a sufficiently low shear strength [2]. Instead, if the impact pressure exceeds a critical value some additional micromechanisms of fracture localization such as shear bands, microrotations and their combinations may be induced. An interesting model of shear banding both in the case of individual event of shear [3] and in the wave propagation processes based on the totality of shear bands have been developed as well [4].

In this work an approach based on the notion of the dynamic deformation and fracture of nonuniform material as a motion of some scale hierarchy of the elementary carriers (EC) of deformation and fracture is developed. An experimental data to date [5] indicate that dynamic deformation is realized in form of a totality of EC moving with different velocities along thee wave propagation direction. The lowest scale level is known to be an atom-dislocation one with EC-dimensions 10^{-8} 10^{-6} cm. The main physical processes herein is the kinetics of point defects, reactions between individual dislocations without taking into account the collective interactions in the dislocation structure. As far as it is known, the checking of similar approach to the precursor decay showed its nonadequacy to the processes following at the microlevel [6].

The second space level of EC is the so-called mesoscopical structure level (0.1-10 mkm), the main specific feature of which is the space and charge heterogenization of dislocation structure on the scale of order the free run length of dislocations [7]. The charge polarization of dislocation ensemble leads to generation of the high-gradient stresses at the mesovolumes boundaries and to the collective interaction.

The next structural level of ED involved the space dimension] 50-500 mkm (2-10 grain sizes) is a superstructural one (SS-level), [7]. The space dimensions of EC belonging to that level are thought to be defined by the long-range stresses induced by the great dislocation charges of mesovolumes. All physical features of that level are defined by the collective interactions of mesovolumes.

Superstructural scale level as well as mesolevel will be shown to play an important role both in inducing of the translational and rotational mechanisms of dynamic deformation and fracture.

Lastly, the macroscopical scale level (10^{-2} - 10^{-1} cm) is the region of the continual description of defect ensembles, continual theory of elasticity and plasticity.

The above classification of the structure levels is generally accepted in physics of plasticity of quasistatic strain rates. As for dynamic and especially shock loading the detailed hierarchic scheme of change of the scale levels is still absent. It is due to the fact that change of the scale levels is still absent. It is due to the fact that the investigation of microstructure behavior in shock wave state "*in situ*" by the conventional optical and electron microscopy techniques is not possible yet. In the iterum there is no confidence that microstructure observed in samples after shock loading corresponds to that at the moment of shock passing. Furthermore, the motion of the EC belonging to the different scale levels has unclear velocity range of their preferable realization, so that it is not seen which scale level gives the greatest contribution into deformation at one or another velocity range. Thus, the interpretation of the microstructural data after shock loading requires the knowledge of the kinetics of EC at every scale level. It suggests that used experimental technique must give a current information about evolution of microstructure in real time, if only at the statistical base. For example, by analogy the mechanics of fluid and gas one can try to use the particle velocity distribution function for characterizing the dynamic behavior of microstructure. Furthermore, at every scale level an independent distribution function must be used because statistical features of EC may depend on their scale level very much.

It is clear also that the independent determination of that function is still impossible even for single scale level because of high-rate character of the processes under consideration. Nevertheless, it seems to be sufficient for numerous practical applications to know only the first and second moments of the particle velocity distribution function, that is the average particle velocity U and particle velocity distribution width ΔU (or square root of the particle velocity dispersion) at one or another scale level. In distinction from distribution function the measuring of the current values of these moments can be provided by the laser interferometry.

In the frames of these requirements the primary objectives of present study were: 1) to reveal and to classify the physical mechanisms of dynamic deformation and fracture and their space and velocity scales. 2) to find the coupling between kinetic characteristics of EC at different levels and macroscopic strength of material. 3) to find the coupling between kinetic characteristics and metallurgical features of material.

EXPERIMENTAL APPROACH

In the kind of material a ductile Cr-Ni-Mo steel was chosen. For providing the different structure states of steel and different conditions of preferable realization of one or another mechanism of dynamic deformation and fracture all specimens were subdivided on three groups *A*, *B* and *C* every of which was subjected to a different tempering (*A* - 200°C, *B* - 600°C and *C* - 650°C for 3 hours) after water quenching at 900°C. Every group of targets of two thickness, 5 mm and 10 mm, was shock loaded under uniaxial conditions within the projectile velocity range 100-500 m/s. The material of impactor was the same as that of the target, the total number of latter was 45 units.

Shock loading of targets was carried out with a 37-mm bore-diameter air-compressed gun. Free surface velocity histories were recorded by using a velocity interferometer the delay shoulder of which provided one-fringe velocity 100 m/s. Laser beam was focused to diameter 100-200 mkm, which corresponds to the superstructural scale level occupying an intermediate position between mesolevel and macrolevel. Taking into account the aforedescribed notion about multiscale character of dynamic deformation the qualitative picture of changing of the plastic front configuration at the several scale levels of two positions of front may be presented as shown in Fig. 1. It is seen that macroscopic particle velocity U_{mc} is the result of averaging of the instantaneous velocities of the superstructure volumes U_{ss} and at the same time the latter is the result of averaging of the instantaneous velocities of mesovolumes U_{ms}. Hence, to obtain the average particle velocity at the macrolevel a number of laser beams must be used simultaneously. Another way is to use any macroscopic gauge, such as quartz, manganin and so on. In this work the capacitor gauges were used to record the macroscopic shock impulse histories of the free surface of targets and to infer the macroscopic strength data. The majority of the experiments were designed to include the material spallation in the later stages of the wave interaction process.

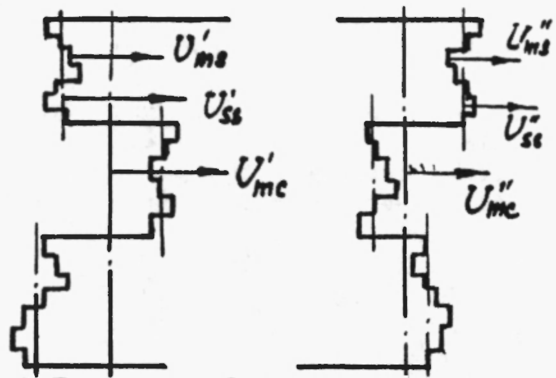

Fig. 1 Two wave fronts of random positions of meso- and superstructural volumes

Besides the local free surface history at the SS-level the velocity interferometer permits to determine once more a very important kinetic characteristics of dynamic behavior of material structure, namely the particle velocity distribution width (the second moment of distribution function) at mesolevel. The process of reflecting of the primary monochromatic laser radiation from target surface may be represented as a generation of a totality of microbeams every of which interacts with one concrete particle of target surface. As a result of that interaction and due to the fact that all particles have different velocities the elementary microbeams acquire the different doppler frequency shifts. It leads to decreasing the degree of monochromaticity of the summary radiation, which is equivalent to widening of its spectrum. The particle velocity distribution width (PVDW) corresponding to this widening can be determined by means of well-known technique [8]. According to [8], the interference picture contrast *I* relates to the particle velocity distribution function *f(U-U)* and is defined by the following expression:

$$I = \int \cos k\ (U-U)\ f\ (U-U)\ dU \qquad (1)$$

W here k is the interferometer constant. Under assumption that f(U-U) has a gauss-form the interference contrast and particle velocity dispersion are related by the equation:

$$I = \exp\left[-\frac{2\ (\Delta u)^2}{\pi^2 k^2}\right] \qquad (2)$$

This equation was used to determine the particle velocity distribution width at the mesolevel (meso-PVDW). A typical interferogram showing the gradual contrast decreasing during the shock loading of 5-mm target of B-steel is presented in Fig. 2a. The meso-PVDW of 29 m/s corresponds to that interference signal if the interferometer constant $k = \lambda_o/2\tau$ equals to 100 m/s pr one fringe. The effect we see in steel are not unique, similar effects are recorded for some of the other materials we have

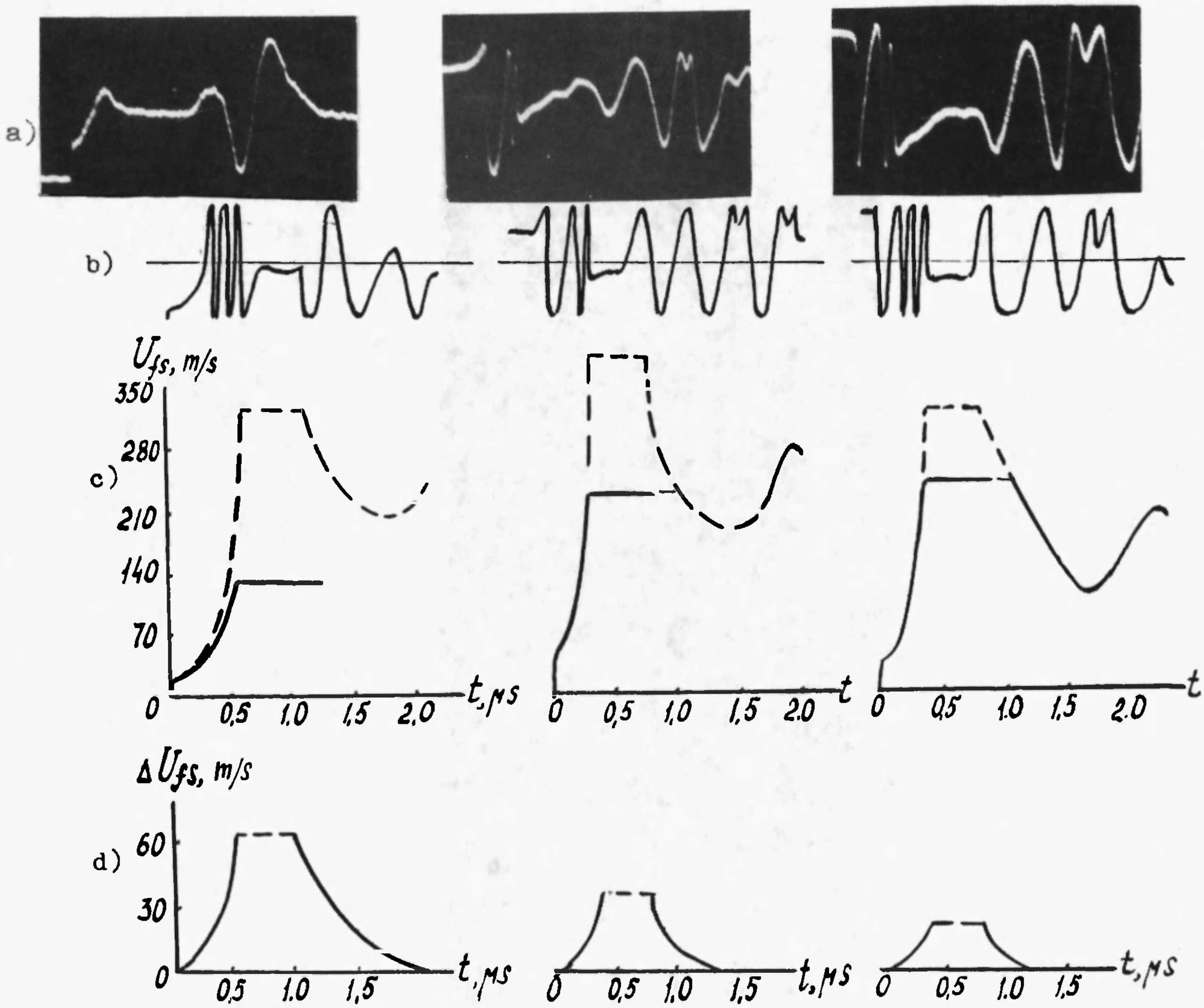

Fig.2. Three kinds of interferograms with different contrast of the signal
a) real interferograms
b) ideal interferograms
c) free surface velocity histories
d) temporal dependencies of particle dispersion

studied such as aluminum and its alloys, copper and so on.

It should be noticed that the separate determination of the average particle velocity at the SS-level and meso-PVDW in the single action of shock loading is possible only if the latter is not so wide that the former could not be observed on its background. As an example in Fig. 3 interferogram is presented where too wide mesovolumes velocity distribution led to a situation when the interference signal amplitude

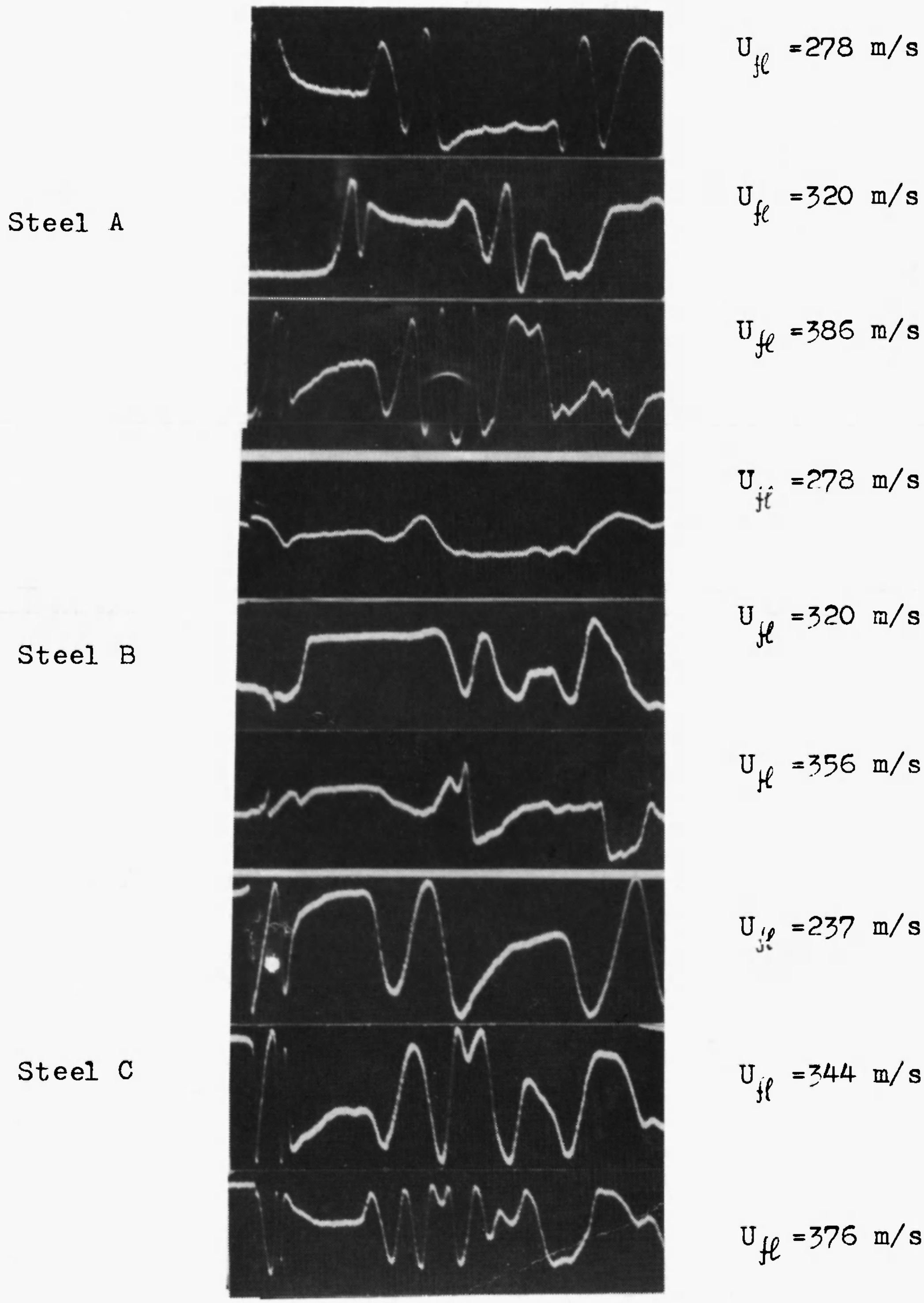

Fig.3. Representative interferograms for three kinds of steel

is decreased to zero long before the plastic front achieved its plateau. It means that average SS-velocity as well as the meso-PVDW remain to be that unknown. The only one can say it is greater than critical value satisfying to unequality:

$$\Delta U_{cr} > 2\ k/\pi \qquad (3)$$

EXPERIMENTAL RESULTS AND DISCUSSION

Shock testing had purpose the determination of two main characteristics of dynamic strength of materials. The first of them is the threshold of the dynamic shear stability. It defines the stress or particle velocity at the plastic front when the steepness of the front slope changes. Whereas the Huguenot elastic limit reflects the transition of the material from elastic range of dynamic strain to plastic that the threshold of shear stability characterizes the change of the resistivity of material to plastic shear due to change of the kind or scale of the structural elements of deformation. For example, it may correspond to transition rom homogeneous dislocation deforming to shear banding or transition of material into structure-unstable state. One must distinct that point from above described decreasing of the interference signal contrast due to particle velocity distribution. According to (2), the interference contrast can be increased or decreased by changing the interferometer constant k. At the same time a threshold of shear stability depends only on the material itself.

The second generally known characteristic of dynamic strength is a spall-strength or "pullback". It defines the resistivity of material to dynamic rupture in a spall zone of target and is a measure of the incipient fracture strength of material. When determined from interferograms that characteristic is local and corresponds to the SS-level. It is of interest to find the coupling that characteristic and mobility of EC at different scale levels, which is characterized by the value of PVDW at these levels. Thereby we could find some transition from micro to macromechanics of dynamically loaded solids.

In Fig. 3 three groups of representative results corresponding to shock loading of steel under consideration is presented together to show the difference in interferograms depending on kind of material.

Before discussion of the quantitative results of testing note that the separate deciphering of the interference signals by using formula (2) within the impactor velocity range 200-500 m/s could be made for A and C kinds of steel only. As for B- specimens, up to impactor velocity 370 m/s all interferograms displayed only onset of the plastic front after which the signal rapidly decreased to zero (as in Fig. 2a). It means that unequality (3) becomes to be applicable long before the plastic front ends. Therefore the quantitative values of the meso-PVDW could not be extracted from interferograms as well as the average free surface velocity at the plateau of the compressive impulse. Nevertheless, the spall-strength can be obtained because to the moment of coming of back front the particle velocity distribution have time to relax to be sufficiently narrow that the free surface velocity could be distinctly recorded by interferometer. In Fig. 4 the dependencies of spall-strength, dynamic shear threshold and the meso-PVDW on temperature of tempering are plotted together for flyer velocity 386 m/s. From

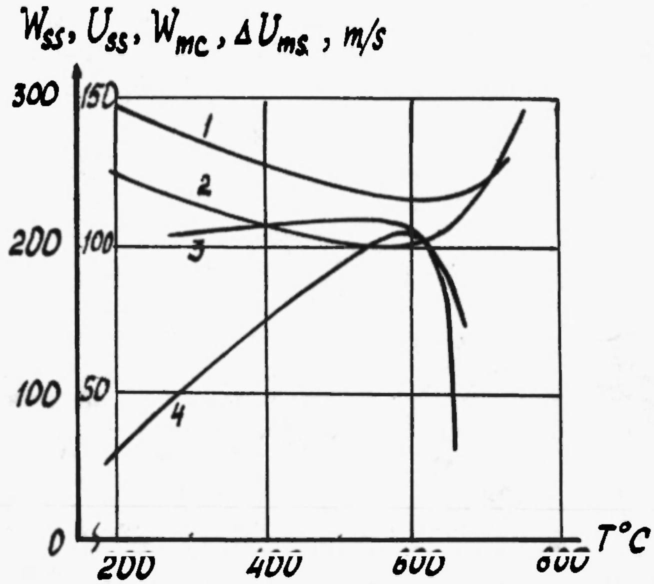

Fig.4. Spall-strength at ss-level(I), at the macrolevel(3),shear threshold (2) and dispersion at mesolevel(4).

these curves some conclusions follow:

i) All dependencies are nonmonotonous.

ii) B-steel has the widest meso-PVDW.

iii) B-steel has the smallest both spall-strength and dynamic shear threshold at the superstructural level.

It is of interest to compare the above dependencies to macroscopic spall-strength presented in the same figure. The latter was obtained by using the capacitor gauges. In distinction from data on local spall-strength (at the SS-level) behavior of the same characteristics at the macrolevel occurred to be quite different. One can see that B-steel has the greatest macroscopical spall-strength. Furthermore, the strength-characteristics for adjacent scale levels appear to be in the opposite phase: the smaller spall-strength at the SS-level the greater that at the mesolevel. On the other hand, it is seen that maximum of macroscopical spall-strength coincides with maximum of the meso-PVDW.

In our experiments we could not provide the measuring of the PVDW at the SS-level. Nevertheless, a general scheme of the relation between scale levels from the point of view of the kinetic characteristics of material and its strength is thought to be presented as follows:

$$\begin{array}{l} \Delta U_{ms} \uparrow \rightarrow W_{ss} \downarrow U_{ss} \downarrow \\ \downarrow \\ \Delta U_{ss} \downarrow \rightarrow W_{mc} \uparrow U_{mc} \uparrow \end{array} \qquad (4)$$

Here, ΔU_{ms} and ΔU_{ss} are the PVDW at the meso- and superstructural level, respectively. W_{ss} and W_{mc} are the spall-strength at the SS-level and macrolevel and U_{ss} and U_{mc} are the shear threshold of SS-level and macrolevel, respectively.

According to that scheme, the increasing of PVDW at mesolevel leads to decreasing the strength at the next level, that is the influence of the velocity distribution on the strength-characteristics of adjacent scale levels appears to be not direct. Velocity distribution at the mesolevel leads to rapid stress relaxation between mesovolumes, which in turn provides a narrow velocity distribution at the next, that is superstructural level. The scattering of the microvolume velocities at any scale level is a way of effective stress relaxation and if the possibility of relaxation at the previous level is "frozen" an intensive local stress are excited between superstructural volumes providing thereby the widening of their velocity dispersion after threshold of shear banding at that level is achieved. The kinetic as well as strength-characteristics of material are transferred from scale level to another in opposite phase.

MICROSTRUCTURE INVESTIGATIONS

Described the relay-like transfer of strength behavior from one scale level to another in opposite phase is a direct consequence of the fact that dynamic deformation and fracture have both localized and multisource nature [9]. Microstructure investigations of ductile steel after shock revealed the presence of the traces of numerous microshear bands oriented along the wave propagation direction. It testifies that inertial forces of microvolumes motion during dynamic deformation play a key role. In distinction from twins these shear bands cross the grain boundaries without changing its direction. Average length of the microshear bands is turned out to be submitted to relation $H_{ms} = \Delta U_{ms} T$ where T is the plastic front risetime. For steel specimens under consideration meso-PVDW achieves the value of 100 m/s and more and the plastic front risetime is 50 ns from where the average shear band length equals to 5 mkm, which corresponds to mesoscopical scale level. A typical micrograph with traces of shear band of mesosopical level in the A-steel is shown in Fig. 5. A different fracture process is realized in B-steel where the greatest meso-PVDW of $\Delta U_{ms} > 100$ m/s was measured. A microstructure study of cross-section of targets revealed a presence of the numerous traces of rotational motion of material. Rotational cells have dimensions about 3 - 7 mkm, which corresponds to mesolevel. As a rule, their interior is damaged, the dimensions of fragments being distributed within 0.1 -0.5 mk. Rotational cells can unite into rings as shown in Fig. 6. The latters are almost one order greater than mesolevel cells and often have a shape of the non-perfect spirals. Depending on tempering regime the rotation cell diameter changes non-monotonously reaching its maximum value at the temperature 600°C, which corresponds to B-steel (see Fig. 7). The character of temporal dependence of mesorotation dimensions is opposite to that of a superstructural one: when the small rotations have a minimum dimensions the large ones occur to be maximal. Similar behavior of rotation can be explained from the point of view of the distribution function at the meso- and superstructural levels. By comparing the dependencies of rotation dimensions with those of PVDW one can see that rotation diameter decreases when PVDW increases. On the upper limit where $\Delta U \rightarrow \infty$ all rotations must transfer into shear bands as a result of giant

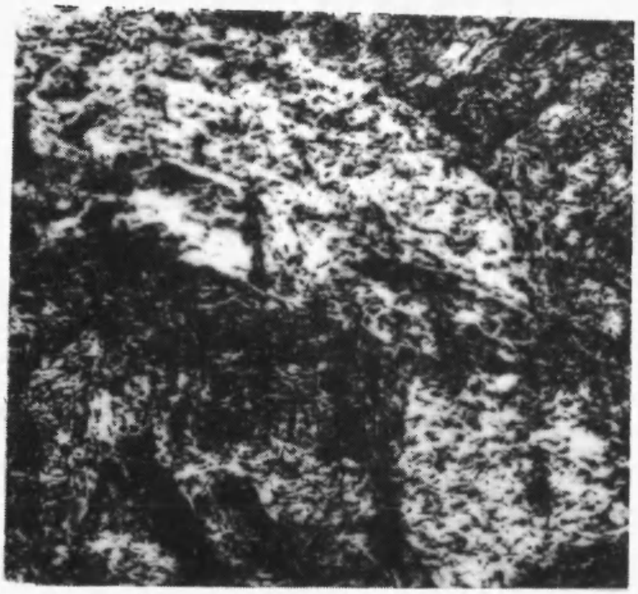

Fig.5. Meso-shears picture in B-steel (xI000).

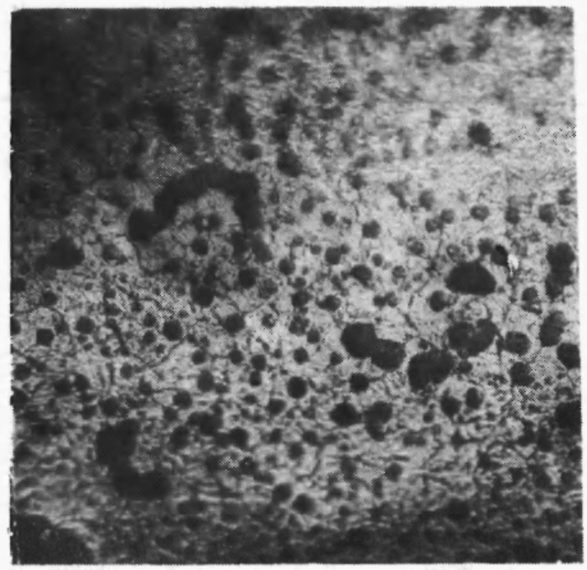

Fig.6. Meso-rotations picture in B-steel (xI000).

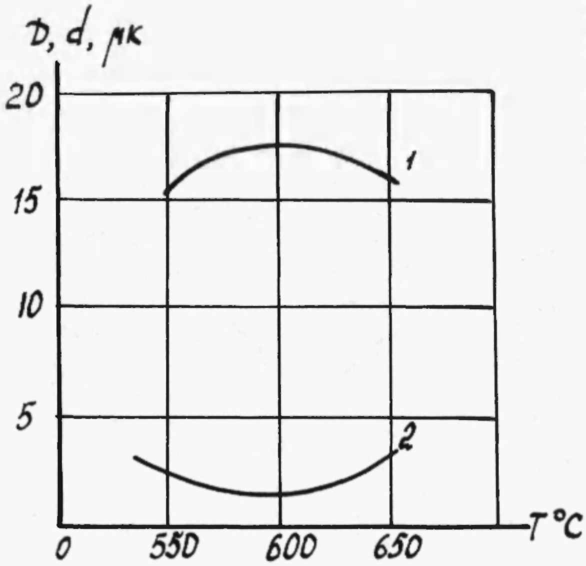

Fig.7. Temperature dependence of rotation diameters for ss-level (I) and mesolevel(2).

diference in the velocities of adjacent mesovolumes. On the other hand, as shown before, with increasing PVDW at the mesolevel the local dynamic strength at that level drops. this leads to decreasing the super-PVDW and to increasing the diameter of rotational cells at the superstructural level. Similar behavior of super-rotations was originally found for steel 45XHMΦA [5]. Thus, a scheme of successive changing the scale of rotational cells may be presented as follows:

$$\begin{array}{l} \Delta U_{ms} \uparrow \rightarrow D_{ms} \downarrow \\ \downarrow \\ \Delta U_{ss} \downarrow \rightarrow D_{ss} \uparrow \end{array} \qquad (5)$$

where D_{ms} and D_{ss} are diameters of rotations at the meso- and superstructural levels, respectively.

This scheme implies that the increasing of meso-PVDW on the one hand, leads to decreasing the super-PVDW and on the another, to decreasing the rotations diameter at the mesolevel. When super-PVDW drops and all supervolumes moves with the same velocities, diameter of rotation at that level increases infinitely, which corresponds to uniform deformation of material. As it follows from scheme presented for reaching an uniform state at the macrolevel the meso-PVDW must be large. In other words, particle velocity non-uniformity at the mesolevel leads to uniform dynamic deformation at the macrolevel.

Decreasing the super-PVDW leads not only to increasing the rotation diameter at that level but to increasing the spall strength as well [5]. It means the structural criteria of dynamic fracture at any scale level must certainly include the particle velocity dispersion.

CONCLUSIONS

The results presented show that dynamic deformation and fracture are realized as multiscale process of microstructure rearrangements in real time. The most sensitive characteristic of these processes is the particle velocity distribution function or its statistical moments. Microvolumes kinetics defines the micromechanisms of dynamic deformation as well as strength at any scale level. In particular, for steel under consideration it was found:

1) There are three scale levels of high-rate deformation: a) mesolevel (1-10 mkm), b) superstructural level 80-300 mkm, c) macrolevel.
2) Shock-induced velocity dispersion of structural elements of adjacent scale levels as well as dynamic strength-characteristics are in opposite phase relatively to each other.
3) Depending on value of the particle velocity dispersion dynamic deformation and fracture at any scale level is realized in form of shear band or rotations, the greater particle dispersion the smaller rotations diameter.
4) Maximal dynamic strength corresponds to the rotational mechanism of dynamic deformation and fracture and minimal - to translational one.

REFERENCES

1. D.R. Curran, L. Seaman, D.A. Shockey, Phys. Today. 1977, vol. 30, p. 46-55.
2. M.Y. Liy, T. Vinh. Proc. Int. Conf. on Constitutive Laws for Eng. Mat. China, 1988, Chong-Qing, Vol. 2, p. 623-627.
3. D.E. Grady, M.E. Kipp. Journal Mech., Phys., Sol., 1987, Vol. 35, N 1, p. 95.
4. D.R. Curran, L. Seamon, Journal de physic, 1986, C-5, T. 46, p. 395.
5. Yu. I. Mescheryakov, S.A. Atroshenko, A.K. Divakov, Proc. of 3 APS-Conf, Shock compression of condensed matter Elsever Sci, publ. B.V. 1990, p. 449.
6. J.N. Johnson, O.E. Jones, T.E. Michaels, Journl. Appl. Phys., 1970, p. 2330-2339.
7. V.I. Vladimirov, In: Voprosy teorii defectov v kristallah. Leningrad, Nauka, 1987, p. 43-56.
8. J.R. Asay, L.M. Barker, Journ. Appl. Phys., 1974, vol. 45, N 6, p. 2445.
9. E.N. Bellinder, V.V. Belyaev, O.B. Neimark, Pisma v GTF, 1989, V. 15, p. 90.