Structural mechanisms of formation of adiabatic shear bands

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ABSTRACT. The paper focuses on the experimental and theoretical study of plastic deformation instability and localization in materials subjected to dynamic loading and high-velocity perforation.

We investigate the behavior of samples dynamically loaded during Hopkinson-Kolsky pressure bar tests in a regime close to simple shear conditions. Experiments were carried out using samples of a special shape and appropriate test rigging, which allowed us to realize a plane strain state. Also, the shear-compression specimens proposed in were investigated. The lateral surface of the samples was investigated in a real-time mode with the aid of a high-speed infra-red camera CEDIP Silver 450M. The temperature field distribution obtained at different time made it possible to trace the evolution of plastic strain localization.

Use of a transmission electron microscope for studying the surface of samples showed that in the regions of strain localization there are parts taking the shape of bands and honeycomb structure in the deformed layer.

The process of target perforation involving plug formation and ejection was investigated using a high-speed infra-red camera. A specially designed ballistic set-up for studying perforation was used to test samples in different impulse loading regimes followed by plastic flow instability and plug ejection. Changes in the velocity of the rear surface at different time of plug ejection were analyzed by Doppler interferometry techniques. The microstructure of tested samples was analyzed using an optical interferometer-profilometer and a scanning electron microscope. The subsequent processing of 3D deformation relief data enabled estimation of the distribution of plastic strain gradients at different time of plug formation and ejection.

It has been found that in strain localization areas the subgrains are elongated taking the shape of bands and undergo fragmentation leading to the formation of super-microcrystalline structure, in which the size of grains is ~300nm. Rotational deformation modes give rise to the high angular disorientations of grains.

The development of plastic shear instability regions has been simulated numerically. For this purpose, we use a recently developed theory, in which the influence of microshears on the deformation properties of materials has

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been studied by the methods of statistical physics and thermodynamics of irreversible processes.

The results of theoretical and experimental studies suggest that one of the mechanisms of the plastic shear instability and localization of plastic strain at high-velocity perforation is related to structural and kinetic transitions in microshear ensembles.

KEYWORDS. Plastic strain localization; Microdefects; Dynamic loading; Numerical modeling.

INTRODUCTION

Thermoplastic instability has long been considered to be a mechanism responsible for plastic strain instability and localization at high loading velocities, [1]. It has been suggested that heat generated in materials during plastic deformation cannot be removed in a short characteristic time, which causes thermal softening and further increase in plastic deformation. The avalanche-type process that is accompanied by a sudden increase in temperature in the area of plastic strain localization is initiated. It has also been found that the temperatures can reach the values high enough to melt the material. Experimental studies of the microstructure of adiabatic shear bands carried out in some works, e.g. [2], have demonstrated that one of the mechanisms of plastic shear band formation is related to multi-scale instabilities observed in microshear ensembles (mesolevel defects).

In the present paper plastic strain instability and localization in the material subjected dynamic loading are considered. The theoretical analysis is based on a previously developed theory, in which the methods of statistical physics and thermodynamics of irreversible processes have been used to study the effect of microshears on the plastic properties of solid bodies, [3, 4].

EXPERIMENTAL STUDY

To investigate the behavior of the material under conditions close to pure-shear dynamic loading, we used a Hopkinson-Kolsky bar. During dynamic deformation, the lateral strain localization area was studied using a high-speed infra-red camera CEDIP Silver 450M.

A special sample shape was proposed to realize pure shear strain localization state (Fig.1). Samples were made from aluminum alloy AlCu4Mg1. Motivation to use this shape of samples is a necessity to have a plane lateral surface for examining the plastic strain distribution by infrared imaging techniques. Scheme for testing and the obtained results are shown in Figs.1, 2.

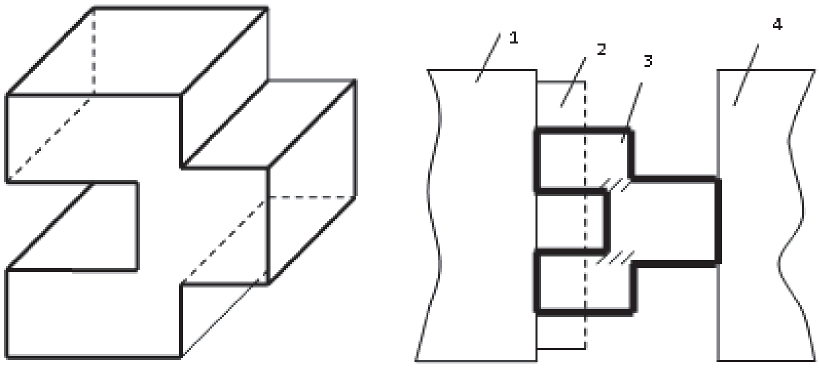

Figure 1: Special shaped sample for testing under conditions close to pure shear, and the scheme of loading with the Hopkinson-Kolsky bar apparatus. 1 – input bar, 2 – frame, 3- sample, 4 – output bar (pure shear state is illustrated by shaded areas).

The analysis of the fracture surface of samples with a transmission electron microscope has revealed the existence of the regions of band and honeycombed structures in the deformed layer in the strain localization areas.
In order to study the properties of materials in a regime close a pure shear under dynamic loading conditions during the split Hopkinson (Kolsky) bar tests, we used the aluminum-magnesium alloy, containing 6%Mg "shear-compression" specimens having symmetrical notches on both sides and proposed in [5].

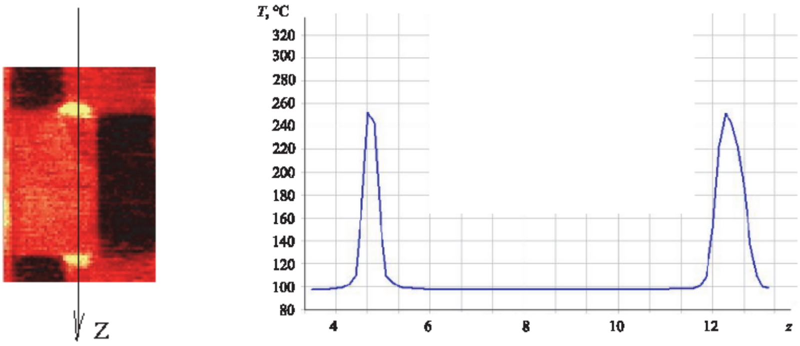

Figure 2: Infrared image of the sample while it was undergoing deformation, and temperature distribution on the coordinate perpendicular to the shear area.

The analysis of the fracture surface of samples with a transmission electron microscope has revealed the existence of the regions of band and honeycombed structures in the deformed layer in the strain localization areas (Fig.3), [6].

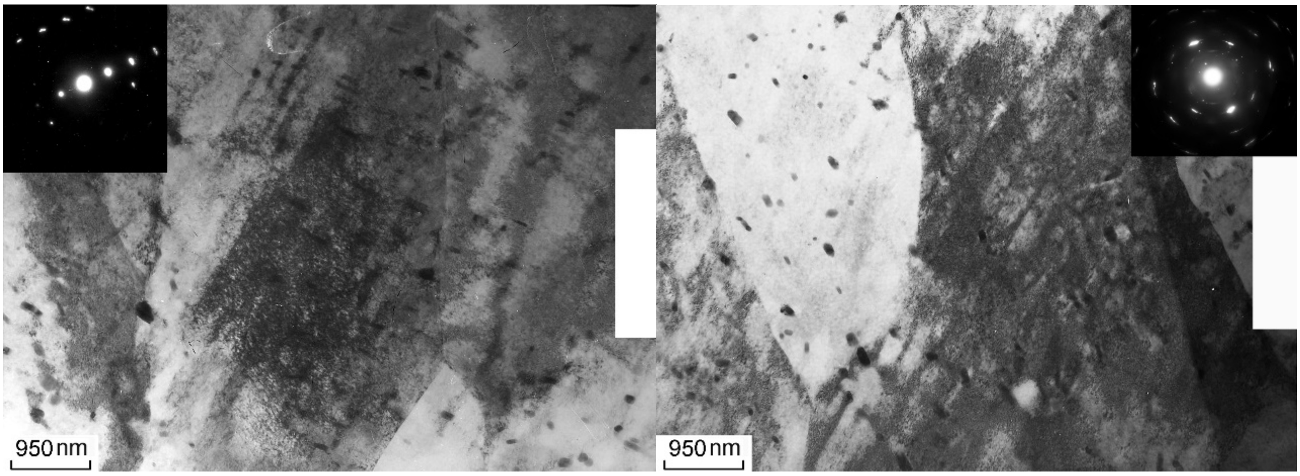

Figure 3: Regions of band and honeycombed structures in the deformed layer in the strain localization areas.

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Application of the high-speed infra-red camera CEDIP Silver 450M allowed us to investigate the distribution of plastic deformation under dynamic loading. The scheme of the experiment, tested specimen and temperature distribution are given in Fig.4. In-situ temperature fields were obtained during the process of deformation. Temperature in the area of plastic strain localization does not exceed ~70°C.
The microstructure of the specimens was analyzed 3D fracture surface roughness using an optical interferometer-profiler, Fig.5. For dynamically deformed specimens, the constancy of Hurst index was observed over a much wider range of spatial scales in the comparison with quasi-static tests.

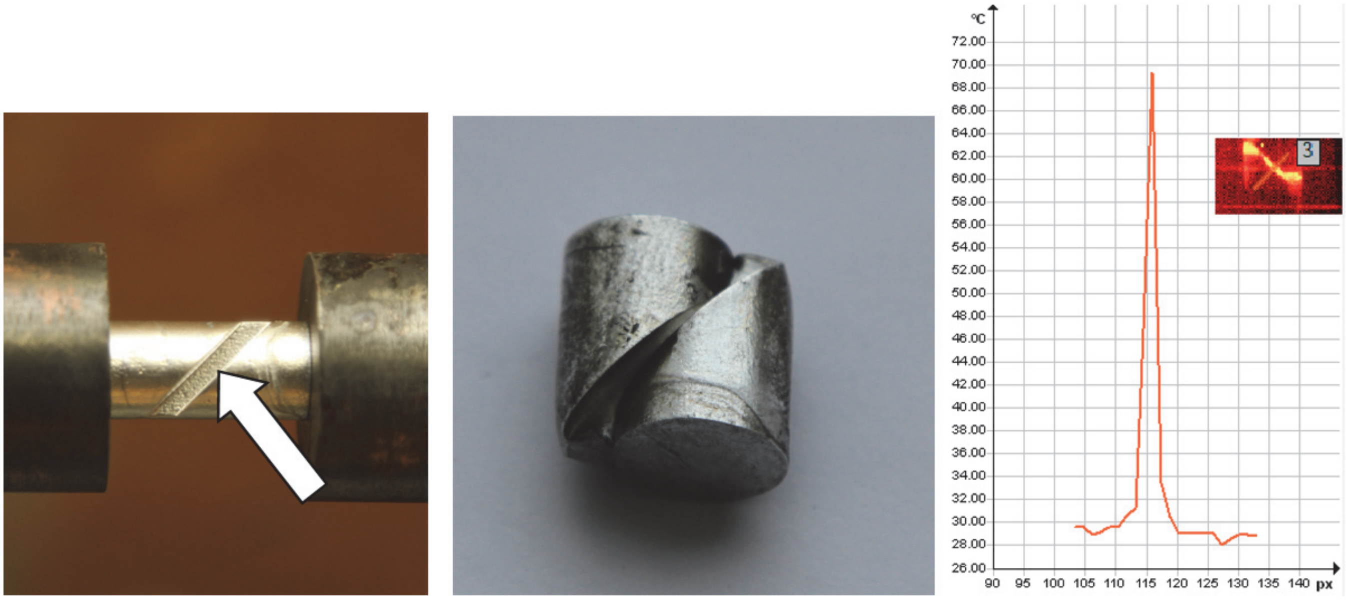


Figure 4: Specimen between the input and output Split Hopkinson (Kolsky) bars. The area indicated by an arrow is in a predominant shear state. Tested specimen. Temperature distribution by coordinate normally to the shear area and infrared image during deformation.

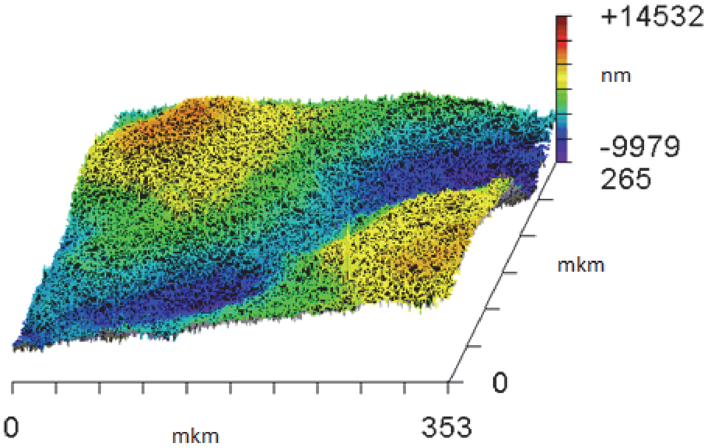


Figure 5: 3D image of the surface of a deformed specimen.

A ballistic set-up was used to realize dynamic penetration test for A6061 alloy samples. In the event of high-speed projectile-target interaction, the failure is realized as plug formation and ejection. The study of the process of target perforation with aid of a high-speed infra-red camera in a real-time mode indicates that the values of temperature in the areas of plastic strain localization are equal to ~100°C at most. Fig.6 shows the infrared images of the plugged hole and the flying pug. The velocity, at which the projectile strikes the target, is 120m/s. The maximum temperature at the hole periphery is 62°C, [7].

Fig.7 represents an infrared picture illustrating the back surface of the target in the process of plug formation.

The process of plug formation and ejection was studied using a laser Doppler velocimeter VISAR. As a result, we obtained the time dependence of the free surface velocity in the area of plug formation and ejection, Fig.8.

After the completion of the test, the microstructure of the deformed specimens was analyzed with the aid of an optical interferometer-profiler profiler New-View 5010 and a scanning electron microscope, [8].

It has been found that the distribution of strain is relatively uniform in the initial penetration region with a smooth mirror-like fracture surface, whereas in the plug formation and ejection regions it becomes essentially non-uniform over the radius of the specimen. The localization of plastic strain occurs in a thin region on the plug generation.

As the plug moves, the relief of the fracture surface becomes rougher and the local heterogeneities of shear deformations increase due to distortion of the internal structure of the material.

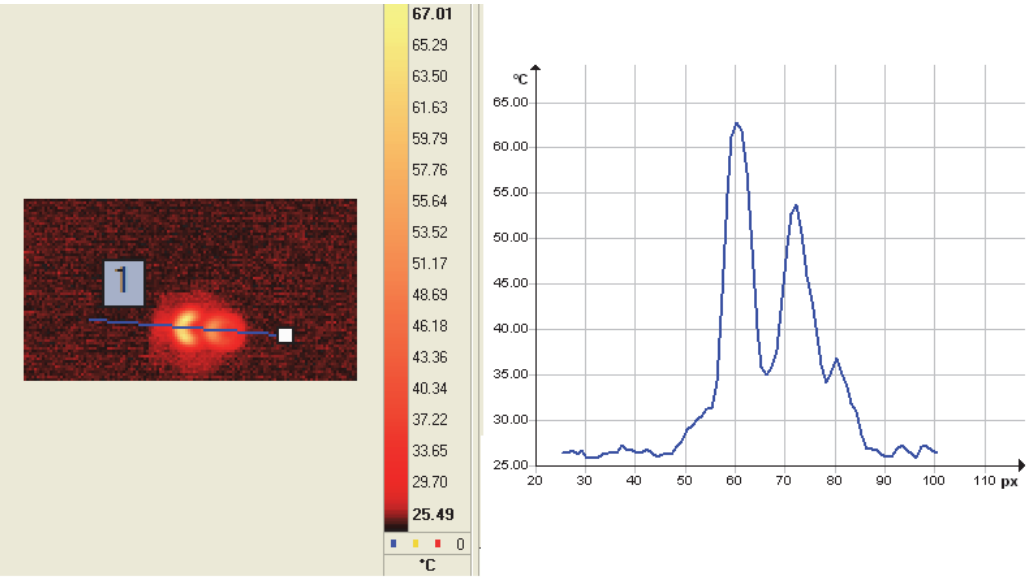


Figure 6: Infrared images of the plugged hole and the flying plug.

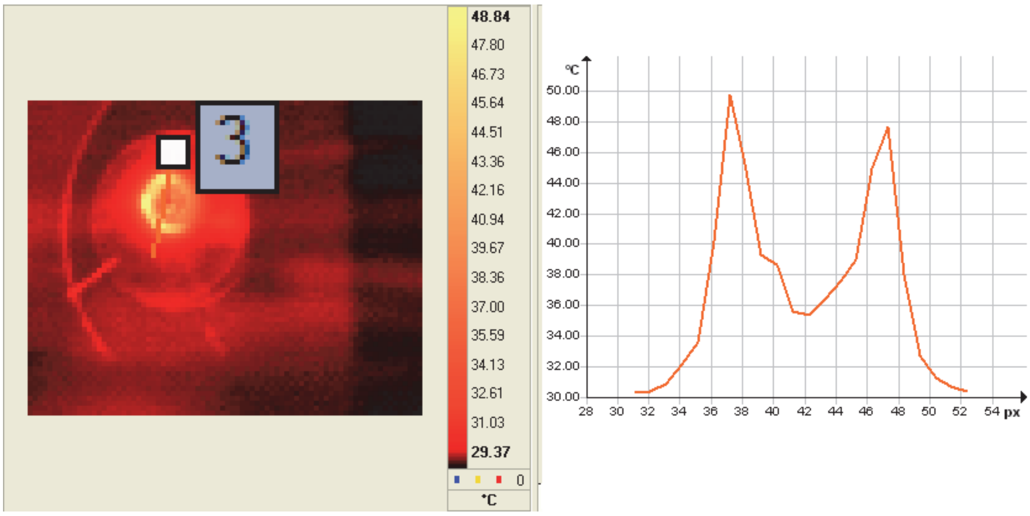


Figure 7: Infrared images of plugging. The maximum temperature at the periphery of the hole is 49°C.

In this case, one can observe the iron pieces of the projectile and grooves occurred due to friction between the rough-polished end-part of the projectile and the material.

The analysis of the rough surface with the scanning electron microscope has revealed the existence of two regions of different morphology: homogeneous in the middle part of the specimen and rougher near its back surface (Fig.9a). The relatively homogeneous rough surface next to the mirror surface corresponds to the shear mechanism of deformation of the material and subsequent coarsening of the deformation structures (Fig.9b).

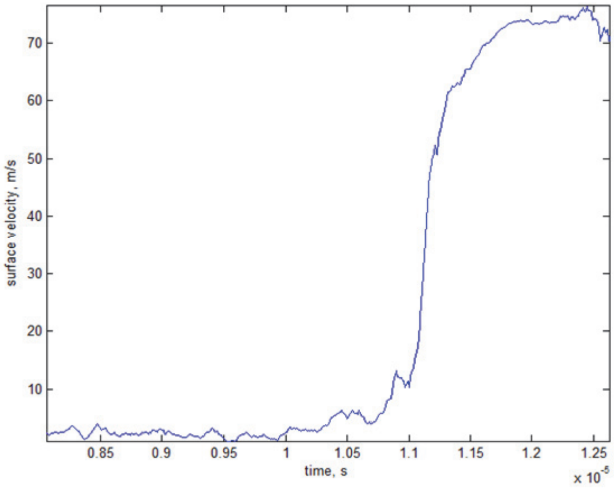
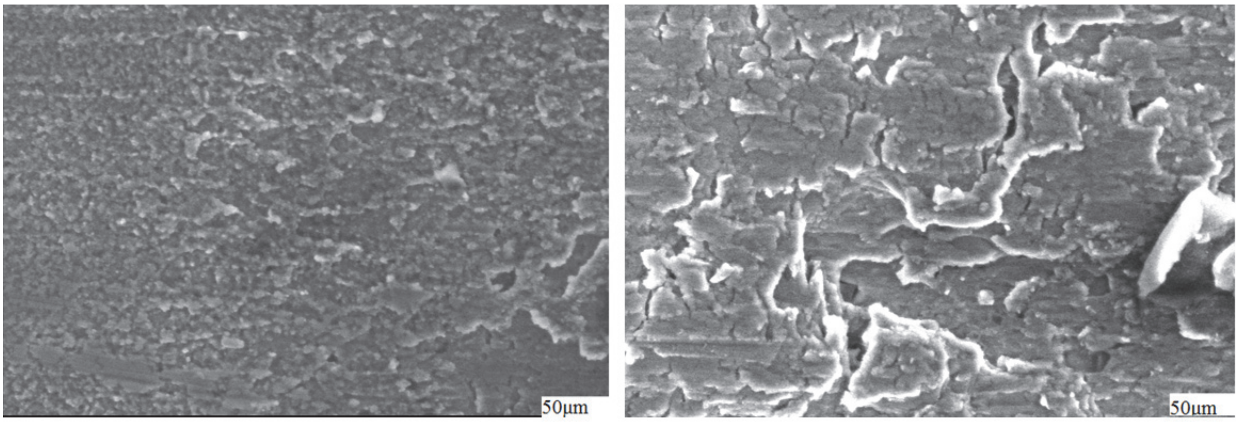


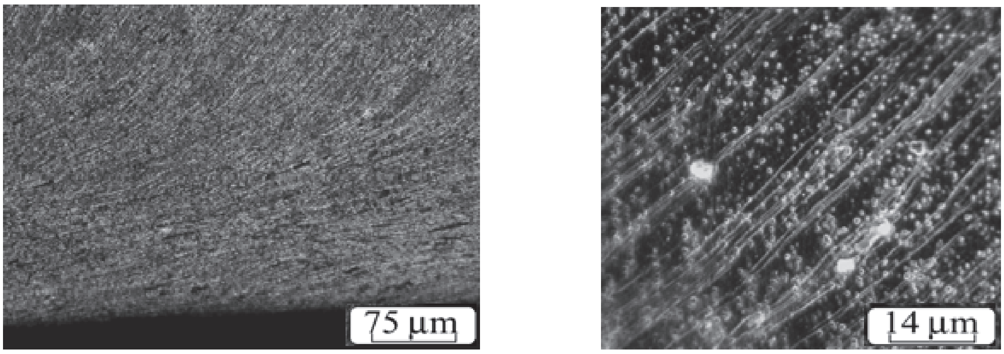
Figure 8: Time dependence of the free surface velocity in the area of plug formation and eject.



a) b)

Figure 9: Rough surface relief corresponding to the plug shear in the specimen. a) rough region near the mirror region, b) rough region at a distance from the mirror region.

The multiscale character of deformation processes taking place in samples subjected to dynamic loading was revealed by selective etching of transverse sections of deformed samples (Fig.10). For example, macroetching in the aqueous solution of 10 % hydrofluoric acid (HF) allowed us to determine the macrolines of the material flow (Fig.10a). Macroetching in the aqueous solution of 1 % NaOH indicates the presence of 15-20 thinner lines between the flow macrolines (Fig.10b).



a) b)

Figure 10: Sample microstructure near the fracture surface for different levels: a) strain macrobands; b) strain microbands. Optical microscopy.

It has been found that the localization of plastic strain occurs in a thin region on the plug formation. It has also been observed that in the areas of strain localization the sub-grains are elongated into bands and then fragmented, forming thus the ultra-crystalline structure with the grain size ~300nm. It is the consequence of the forming of the rotational deformation modes and the high-angle disorientations of grains.

MODELING

The mechanisms of plastic shear instability and localization of plastic deformation (in the quasi-uniaxial statement) have been simulated numerically, and the peculiarities of the kinetics of microshear accumulation in the material have been analyzed.

We consider the deformation of a plane layer under simple shear loading. One side of the layer is rigidly fixed, and the other side is moving with a constant velocity. During the process of high-speed deformation of the material, a structural transition in the microshear ensemble occurs in the local area. This transition is characterized by the jump in the microshear density parameter (Fig. 11a), which leads to abrupt change in effective characteristics of the material, in particular, to sharp decrease in the effective viscosity, and, as a consequence, to an increase in the plastic deformation and stress relaxation rates, and finally to decrease in the shear resistance in this area (Fig.10b).

Twisting deformation of thin-wall cylindrical specimens was simulated numerically according to the experimental scheme of pure shear testing in quasi uni-axial formulation. Fig.12 represents the graph illustrating the distribution of plastic strain localized in the narrow central part of the specimen.

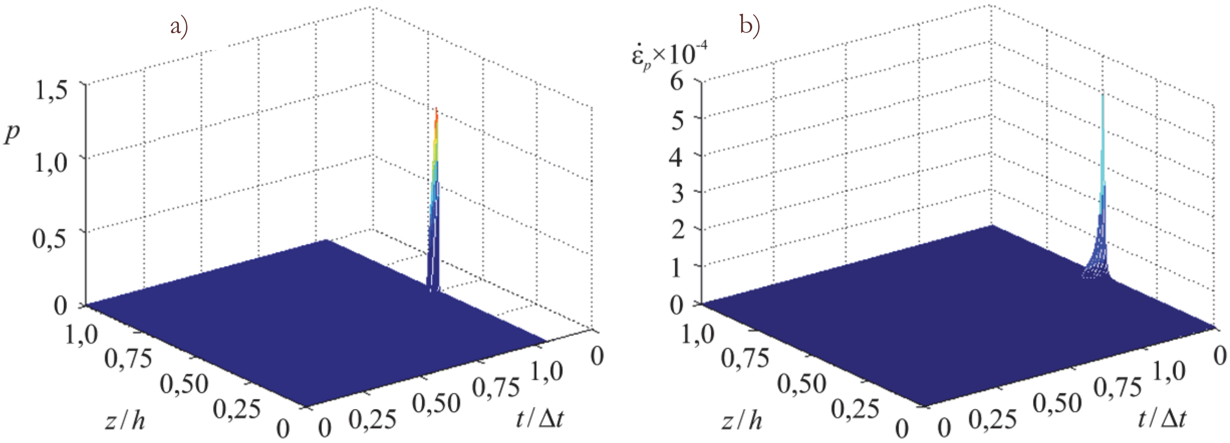


Figure 11: Distribution of a) microshear density parameter, and b) plastic deformation rate.

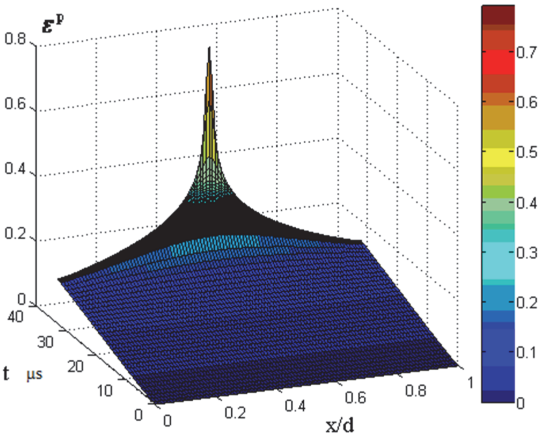


Figure 12: Evolution of plastic deformation with time along the specimen.

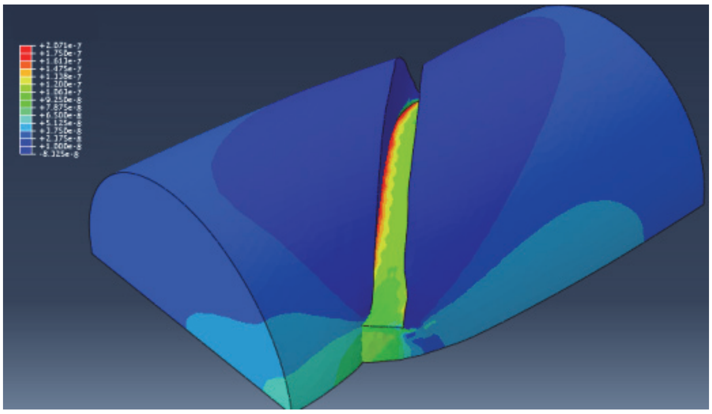


Figure 13: Numerical results. Distribution of microshear density parameter.

In Fig. 13 shown results of 3D simulation, which was made using ABAQUS.

Numerical simulations allowed us to determine temperature distribution on the back surface of the target during the process of plug formation and ejection, Fig.14.

Temperature fields on the back surface of the sample during the process of plug formation and ejection are close to those found experimentally.

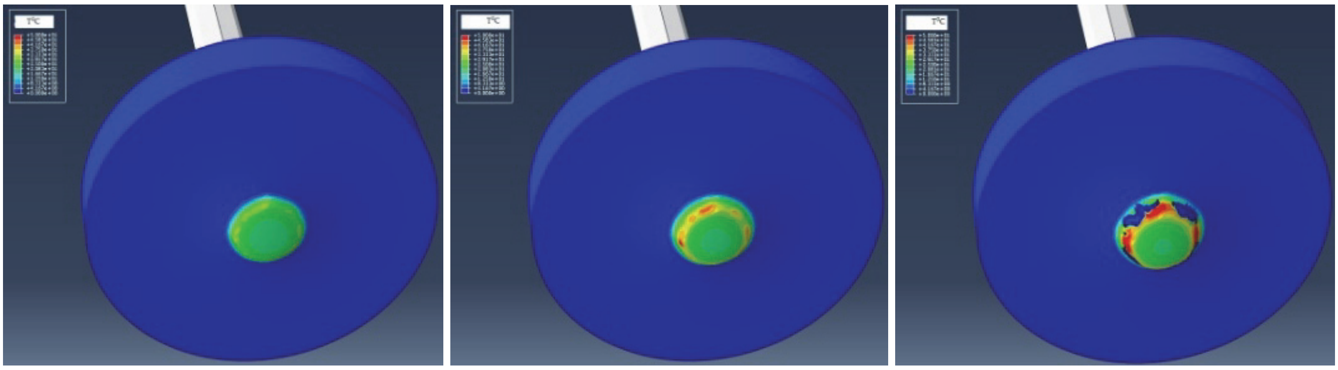


Figure 14: Time evolution of temperature distribution on the back surface of the sample.

CONCLUSIONS

Theoretical study and original experimental data allow us to suggest that one of the mechanisms of plastic shear instability and plastic strain localization observed in the high-speed loading tests is caused by the collective multiscale behavior in the microshear ensembles qualified as non-equilibrium structural-scaling transition. This mechanism leads to the pronounced structural relaxation leading to the plastic strain localization and is independent on conventionally used assumption concerning the autocatalytic temperature effect on the viscosity decrease. Structural analysis of material in the strain localization area supported this mechanism of structural relaxation and the influence on strain localization as the precursor of adiabatic shear band formation.

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