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Physics of Extreme States of Matter — 2012

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This compendium is devoted to investigations in the fields of thermal physics of extreme states of matter and physics of high energy densities. Different models and results of theoretical calculations of equations of state for materials at high pressures and temperatures, physics of shock and detonation waves, experimental methods of diagnostics of ultrafast processes, techniques of intense energy fluxes generation, interaction of intense laser, x-ray and microwave radiation, powerful particle beams with matter, low-temperature plasma physics, issues of physics and power engineering, as well as technology projects are considered. The majority of the works has been presented at the XXVII International Conference on Equations of State for Matter (March 1–6, 2012, Elbrus, Kabardino-Balkaria, Russia). The edition is intended for specialists in physical and technical problems of power engineering.

The conference is sponsored by the Russian Academy of Sciences and the Russian Foundation for Basic Research (grant No. 12-02-06011).

The editorial board announces with deep regret the death of the colleague and friend, Prof. Anatoliy Inderbievich Temrokov (January 17, 1942–February 22, 2011), who was the initiator, organizer, and chairman of the I All-Union Conference on Equations of State for Matter (together with Prof. D. A. Kirzhnits), the unchallenged chairman of 25 subsequent Conferences on Equations of State for Matter and Interaction of Intense Energy Fluxes with Matter.

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THE STRUCTURE OF SUPERELASTIC&PLASTIC SHOCK WAVE

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Last year we have reported the observation of superelastic shock waves [1, 2]. These waves move with the "elastic" velocity (in a continual approach this velocity is defined by the elastic constant $K + \frac{4}{3}G$ contrary to the velocity of plastic wave, which is defined by the elastic constant K). Here K and G are bulk and shear moduli of a material. However, the pressure behind the shock wave is several times the classical Hugoniot elastic limit. Such waves have been observed in experiments for example [3–7]. The motion of a shock wave and the subsequent plastic shock are correlated. Now we present the structure of superelastic&plastic shock wave on the base of molecular-dynamic simulation [2, 8]. The calculations correspond conditions of the experiment [3]: a laser pulse with duration of 120 fs and a power of $7.7 \cdot 10^{13}$ W/cm^2 (the absorbed energy is 2.6 J/cm^2) affects the aluminum film.

The initial elastic shock wave (ElSW) begins to form well before the maximum of compression wave on the front of melting (see Fig. 1, 2).

The thermal wave leaves far forward at a two-temperature stage due to the fact that the thermal diffusivity of the electron subsystem $\chi_e = \kappa_e/c_e$ is much more than the one of a whole substance $\chi = \kappa_e/c$ (here c_e and c are the heat capacities of electron subsystem and whole matter respectively, and the heat conductivity of a matter is determined dominantly by the electron heat conductivity κ_e). When passing through the melting front the pressure profile becomes steeper. This creates the seed from which the leading elastic shock wave develops (Fig. 2).

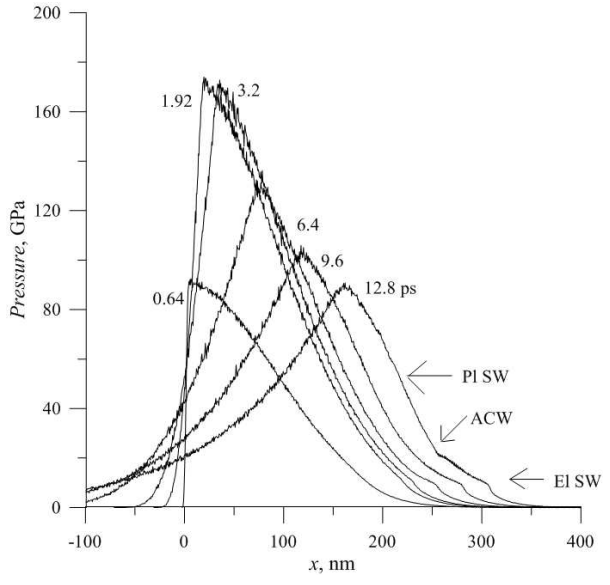

Figure 1. Pressure profiles at short time. The numbers on the curves specify time in ps. The arrows indicate the sites with the greatest steepness of the pressure profile of which elastic (ElSW) and the plastic wave (PlSW) shock waves are further formed, and the break of the pressure profile at the boundary of the elastic and plastic zones from which additional compression wave radiates (ACW)

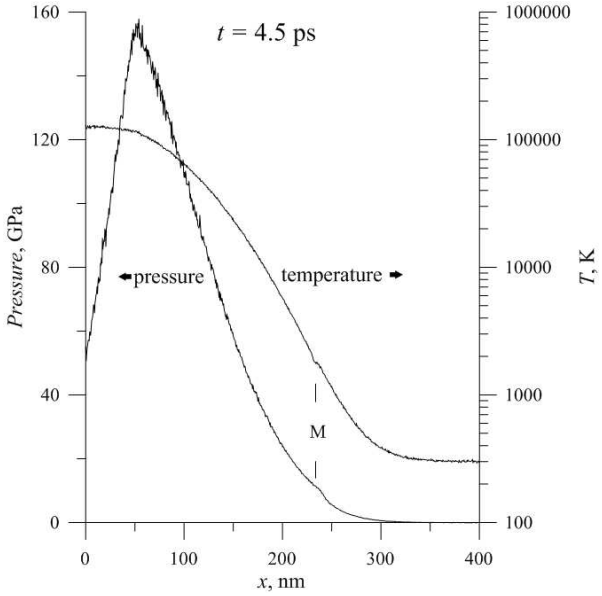

Figure 2. Pressure p_{xx} and temperature at $t = 6.4$ps. Lines M indicated position of melting front

The pressure on the elastic shock wave at this time is close to the Hugoniot elastic limit (HEL, for aluminum the part of GPa). Then the elastic shock quickly passes the front of melting.

Emerging plastic shock (PlSW) overtakes and pushes the emerging elastic one. The pressure in the metastable elastically compressed material behind the elastic shock rises to a value several times larger than HEL (in aluminum up to tens of GPa). Ahead of the PlSW there arise additional compression waves (ACW) (see Fig 3, 4). The fact that the material remains elastically deformed after the first front and experiences plastic deformations on the second front can be seen from the profiles of shear stress (dashed lines in Fig. 3 and following figures), which is proportional to the pressure at uniaxial shear in an elastic material and is reset to zero by plastic deformations. The pressure on ACW is higher than on the ElSW. They move also in an elastic medium. Following one after another, these waves are catching up ElSW and push it (see Fig. 5).

In the advanced stage long time elastic shock moves with its "elastic" rate (taking into account the contribution of shear stresses under uniaxial compression) and plastic shock moves together with it almost simultaneously. Then the plastic wave gradually loses its

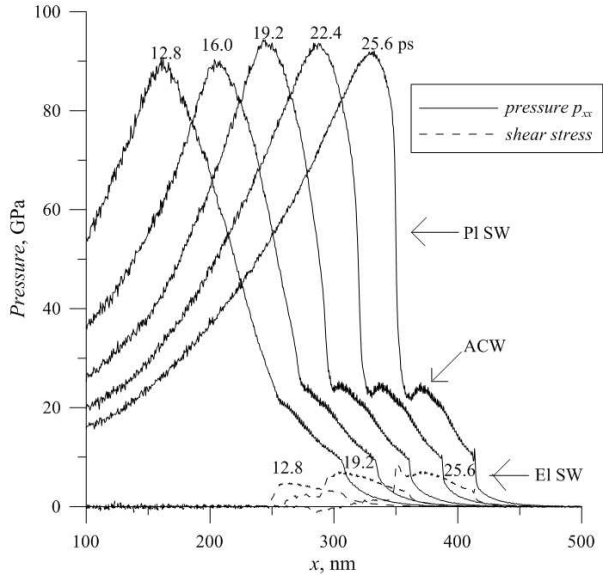

Figure 3. Formation of elastic (ElSW) and plastic (PlSW) shock waves and additional compression (ACW) wave between them. Pressure profiles (continuous lines) and shear stress (shaped lines) are shown. The numbers on the curves specify time in ps.

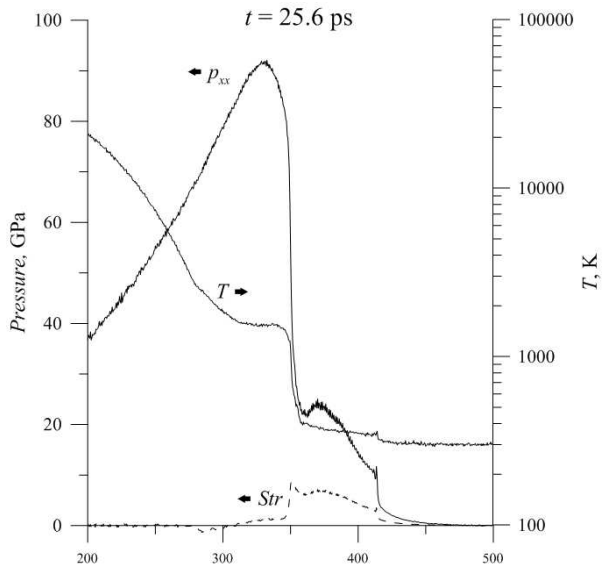

Figure 4. Pressure p_{xx} and shear stress and temperature at $t = 25.6$ ps

intensity and slowed down (see Fig. 6). Finally the plastic wave stops. Plastically deformed layer of a final thickness is thus fixed.

The resulting graphics of a motion of elastic and plastic shock waves and additional compression waves in comparison with the shock wave in two-temperature hydrodynamic calculations (2T-HD) without taking into account the elastic corrections are shown in Fig. 7. With the coexistence of several compression waves there are plotted the coordinates of stronger one. We can see the jumps in the graph of compression waves in passing from one wave to another. At large times when the plastic shock wave decays it is shown the position of the front of plastic deformations.

The simulation results well correspond to results of

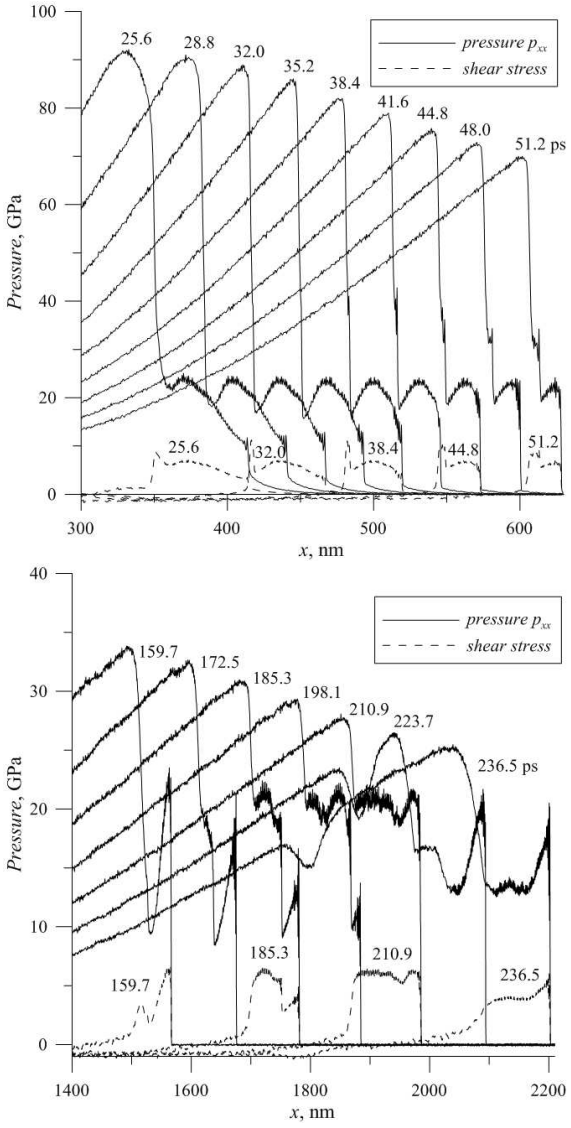

Figure 5. Superelastic&plastic wave structure at medium times.

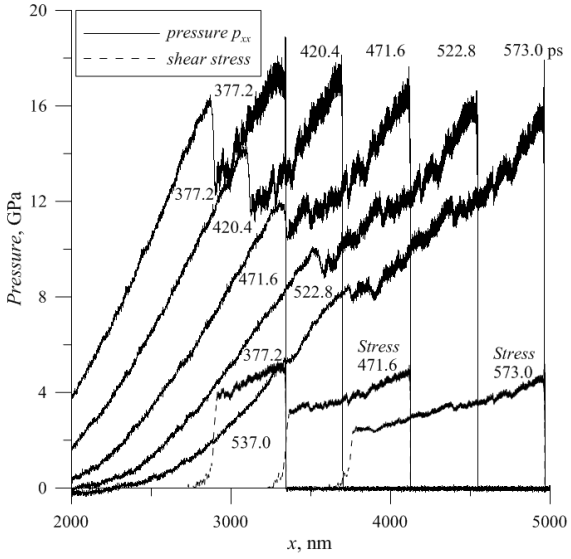

Figure 6. Attenuation and braking of a plastic wave on large times. Pressure profiles (continuous lines) and shear stress (shaped lines) are shown. The numbers on the curves specify time in ps.

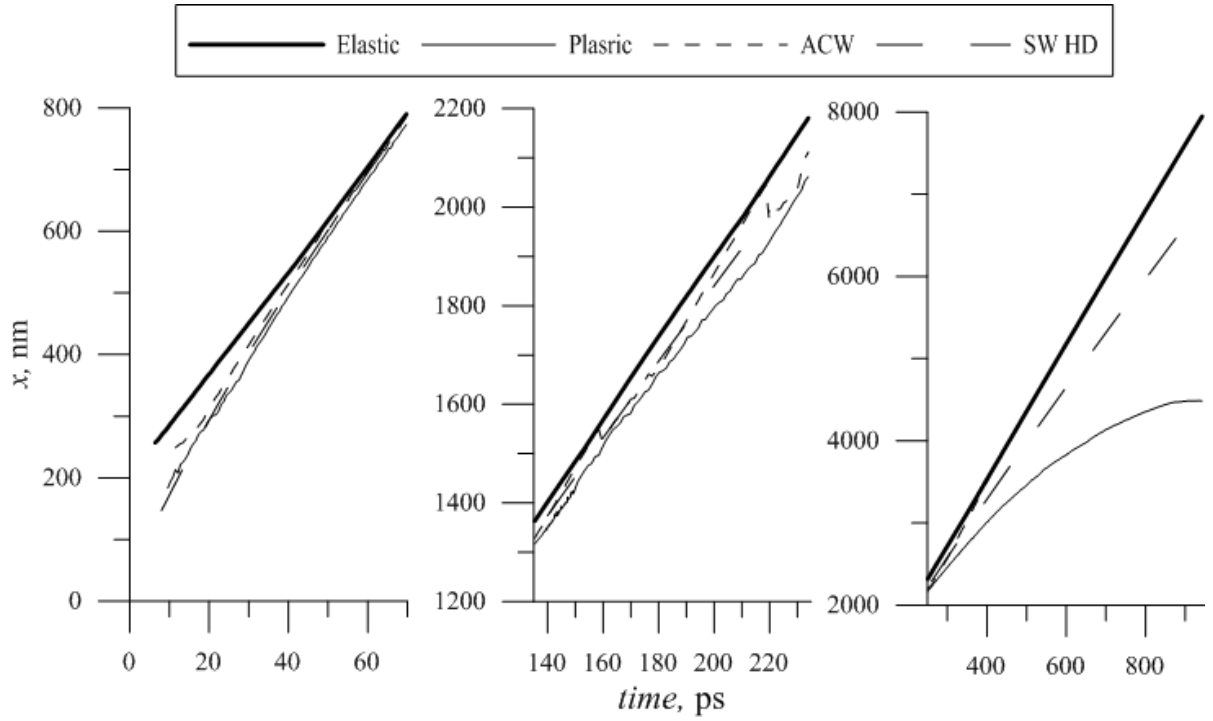

Figure 7. The elastic SW (thick lines), the plastic wave / plastic deformations front (thin lines), additional compression waves (short dashed lines) and SW position from 2T-HD calculations (long dashed lines)

experiments [3] (see [2, 8]). At large times the position of ElSW corresponds to the results of experiments [4], which have been performed with the same characteristics of the laser pulse as [3], but with thicker films.

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1. Inogamov N. A., Khokhlov V. A., Zhakhovskii V. V. // Physics of Extreme States of Matter—2011 / Ed. by Fortov V. E., et al. Chernogolovka: IPCP RAS, 2011. P. 11–14.
2. Inogamov N. A., Zhakhovskii V. V., Khokhlov V. A., Shepelev V. V. // JETP Lett. 2011. V. **93**. P. 226–232
3. Evans R., Badger A. D., Fallies F., Mahdieh M., and Hall T. A. // Phys. Rev. Lett. 1996. V. **77**. P. 3359.
4. Huang Li, Yang Y., Wang Y., Zheng Z. and Su W. // J. Phys. D: Appl. Phys. 2029. V. **42**. P. 045502.
5. Agranat M. B., Anisimov S. I., Ashitkov S. I., Zhakhovskii V. V., Inogamov N. I., Komarov P. S., Ovchinnikov A. V., Fortov V. E., Khokhlov V. A., Shepelev V. V. // JETP Letters. 2010. V. **91**. P. 471 [Pis'ma v ZhETF. 2010. V. **91**. No. 9 P. 517–523]
6. Ashitkov S. I., Agranat M. B., Kanel' G. I., Komarov P. S. and Fortov V. E. // JETP Letters. 2010. V. **92**. No. 8. P. 516 [Pis'ma v ZhETF. 2010. V. **92** No. 8. P. 568–573]
7. Whitley V. H., McGrane S. D., Eakins D. E., Bolme C. A., Moore D. S., and Bingert J. F. // J. Appl. Phys. 2011. V. **109**. P. 013505
8. Inogamov N. A, Khokhlov V. A., Petrov Yu. V., Anisimov S. I., Zhakhovskii V. V., Demaske B. J., Oleynik I. I., White C. T., Ashitkov S. I., Khishchenko K. V., Agranat M. B. and Fortov V. E. // AIP Conference Proceedings. 2012. V. **1426**, in press.

HIGH-RATE DISLOCATION PLASTICITY AND SHOCK WAVES ATTENUATION IN METALS

Mayer A.E.,[*1] ***Khishchenko K.V.,***[2] ***Levashov P.R.,***[2] ***Mayer P.N.***[1]

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Introduction. In the present work, we develop the theoretical approach for high-rate dislocation plasticity proposed in [1–3]. Plastic strain rate is found out through the dislocations sliding; equations for kinetics and motion of dislocations contain pseudo-relativistic terms.

In papers [1–3] a good agreement had been obtained with experimental data for elastic precursor shape and height for a number of metals (copper, aluminum, iron, titanium); but an agreement for the unloading wave shape was not so good. It should be note that similar problem with the unloading wave modeling was met by other researches as well [4]. Possible reason of such deviation is a formation of various dislocation structures, as it was pointed out in [3].

As opposed to [1–3], more complex kinetic equations are used here, which take into account the mobile dislocations and another type of dislocations, which