Sound Velocities and Shear Strength of Shocked U within 10-250 GPa

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Abstract. The paper presents the results of measurements using the manganine gauge method within $10 \leq \sigma_{xx} \leq 100$ GPa and the optical analyzer technique at $90 \leq \sigma_{xx} \leq 250$ GPa of longitudinal and bulk sound velocities at high-rate deformation in α– and γ–phase ranges, as well as in γ–liquid phase transition range and U melt. Changes of all elastic moduli, including the shear modulus, are determined along the Hugoniot at high-rate strain of U in α– and γ–phases.

Introduction. Verification of recent elastic-viscous-plastic models and multiphase equations of state requires systematic experimental data on shock, isentropic, and isothermal compressibility of metals and alloys, and uranium in particular, in a wide range of pressures, temperatures, and energy densities including shock-induced melting.

The review of experimental and theoretical investigations into specific features of shock and isothermal compressibility of uranium in the regions of polymorphous, electron, and phase (melting) transitions is provided in [1]. This review covers all publications till 2005, including the results on:

- ab-initio calculations of possible polymorphous, electron, and phase transitions [2-5];
- isothermal compressibility [6-10];
- shock compressibility with discrete [11-13] and analogue [1,14,15] diagnostics of wave processes;
- systematic metallographic and X-ray diffraction studies of samples exposed to plane and spherical shock loading [1,16];
- semiempirical multiphase equation of state of U [17,18].

It appears important to experimentally specify the conditions of shock-induced melting of unalloyed uranium directly at the strong shock wave front. Such refinements are possible on the basis of measurements along the Hugoniot of longitudinal $C_\ell(\sigma_{xx})$ and bulk $C_B(\sigma_{xx})$ sound velocities when determining the amplitude of shock loading σ^*_{xx} corresponding to disappearance of differences between C_ℓ and C_B at $\sigma_{xx} \geq \sigma^*_{xx}$, as well as by direct pyrometric measurements of temperatures in shocked and partially unloaded into the window material uranium. The importance to specify the conditions for the onset of shock-wave melting of U is caused by the 1.5-fold difference in temperature in the available [17-19] semi-empirical multiphase equations of state for this material.

The purpose of the present investigation is to obtain experimental data on longitudinal $C_\ell(\sigma_{xx})$ and bulk $C_B(\sigma_{xx})$ sound velocities within the shock-wave loading range $10 \leq \sigma_{xx} \leq 250$ GPa associated with high-rate strain of U in solid states and its melting at the shock wave front.

Material, samples, and conditions of shock loading. Samples of unalloyed U of technical purity with the content of the main material no less than 99.6% were studied. The main impurities are C, Si, Fe and Ni. The density is 18.93 g/cm^3, the longitudinal and bulk sound velocities at ambient conditions are 3.45 km/s and 2.43 km/s. The samples were shaped as four-stage cylindrical wedges with ∅60 mm. The sketch of the measurement unit is shown in Fig. 1. The experiments were made with plates-impactors having different thicknesses and velocities, which were accelerated into vacuum by HE charges of different types and thickness. Chloroform $CHCl_3$ was used as indicator. The diameter of optical installation in the experiments was 20 mm. Each optical fiber serviced its own sector corresponding to a certain thickness of the staged sample.

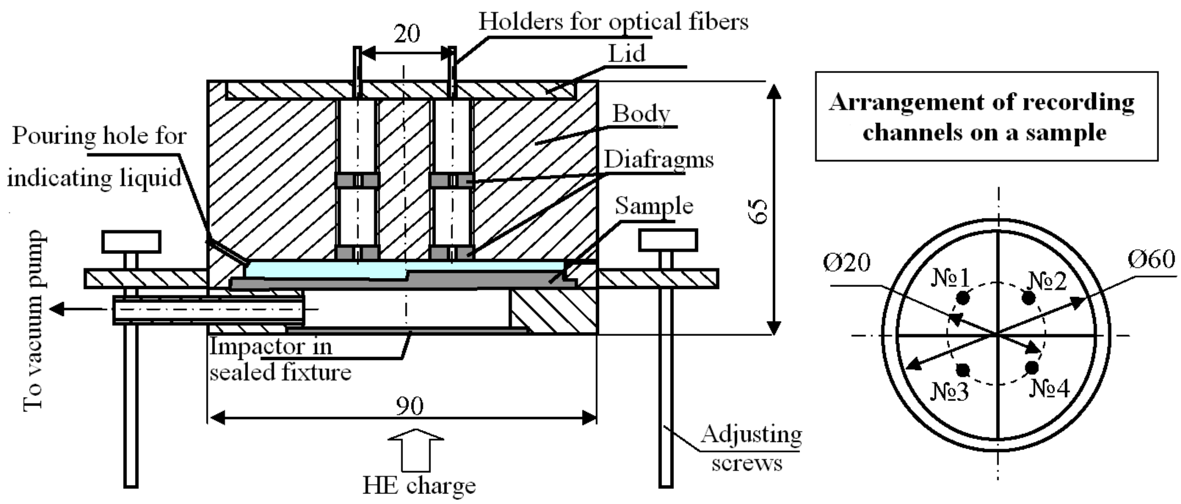
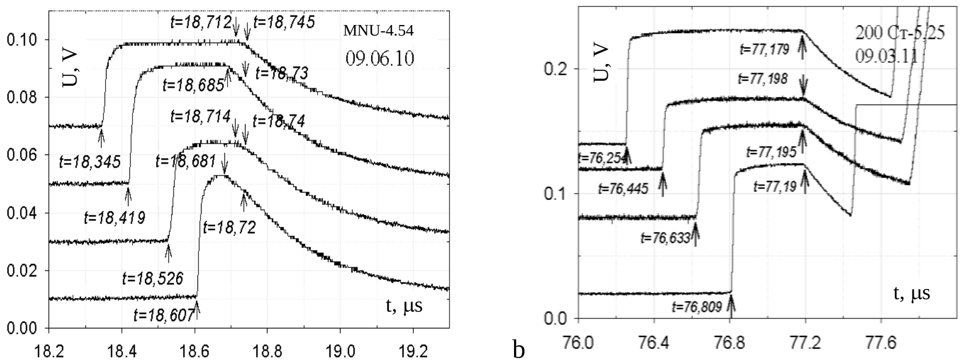


Fig. 1 – Sketch of the measurement unit (not to scale).

Diagnostic techniques. The optical analyzer technique (OAT) is based on recording of variation of the luminous intensity of the shock front in the indicator positioned after the samples under study, when the former is overtaken by rarefaction waves. A strong dependence of the luminous intensity on the loading amplitude is used. According to the data provided in [20-22], at optimal setup and in case of obtaining high-quality oscillograms, the method allows one to determine the velocities of rarefaction waves with an accuracy of ±3%.

The advantages of the method are high sensitivity, high time resolution, possibility of continuous recording of the processes during long periods of time, and creation of multichannel recording systems. The drawback is the difficulty to use the method at low pressures due to complicated recording of weak luminosity of low-amplitude shock waves in the indicator. In the lower loading range at $10 \leq \sigma_{xx} \leq 100$ GPa the method of low-resistivity (40 mΩ) manganine sensors was used.

Typical oscillograms of signals obtained using the optical analyzer technique in experiments # 129 and # 166 are shown in Fig. 2.



a b

Fig. 2 – Oscillograms of explosive experiments on sound velocities measurements for uranium
a) – experiment # 129 of June 09, 2010, MNU-4.54, σ^U=185.3 GPa; b) – experiment # 166 of March 09, 2011, 200 St-5.25, σ^U=224.4 GPa.

Results and their discussion. All experimental data obtained at VNIITF using the MD and the OAT methods are provided in Fig. 3. For comparison, the graph also shows the results of electric contact measurements made at VNIIEF in 1967 (A.I.Funtikov) and in 1979 (A.A.Bakanova, V.N.Zubaryev, and R.F.Trunin), as well as data obtained using the OAT (M.V.Zhernokletov, A.E.Kovalyev et al, 2011) and the LI method (A.L.Mikhaylov et al).

The range σ_{xx} = 85−100 GPa corresponds to the α–γ phase transition, as confirmed in 1985 during systematic research of recovered U samples after explosive loading at VNIITF and VNIINM. Melting of uranium at the shock wave front is determined at σ_{xx} = 130−160 GPa according to the OAT data obtained at VNIIEF, at σ_{xx} = 160-190 GPa according to the OAT data obtained at VNIITF, and at σ_{xx} = 185-205 GPa according to Fabry-Perot laser-interferometry data obtained at VNIIEF.

The experimental data on the longitudinal $C_\ell(\sigma_{xx})$ and bulk $C_B(\sigma_{xx})$ sound velocities measured along the Hugoniot make it possible to derive the change of all elastic moduli in shocked state, in particular, Poisson ratio $\nu=\left[3-(C_\ell/C_B)^2\right]/\left[3+(C_\ell/C_B)^2\right]$, elasticity modulus $E=\rho C_\ell^2(1-2\nu)(1+\nu)/(1-\nu)$, bulk modulus $K=\rho C_B^2$, and shear modulus $G=E/2(1+\nu)=\rho C_\ell^2(1-2\nu)/2(1-\nu)$. These results are provided in Fig. 4.

The data plotted in Fig. 4 imply that the increase of shear strength for U under its compression is realized only in a relatively low range of longitudinal stress at $\sigma_{xx} \le 20$ GPa. At higher amplitudes of shock loading, softening due to shock-wave heating begins to prevail over strengthening due to compression.

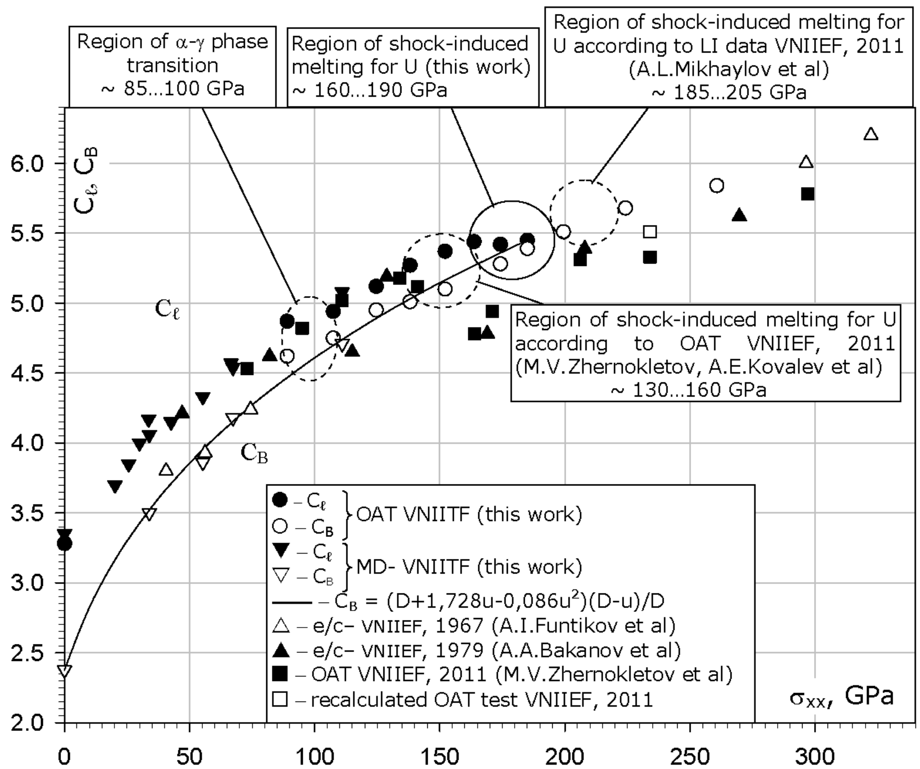


Fig. 3 –Longitudinal C_ℓ and bulk C_B sound velocities versus shock compression stress for uranium.

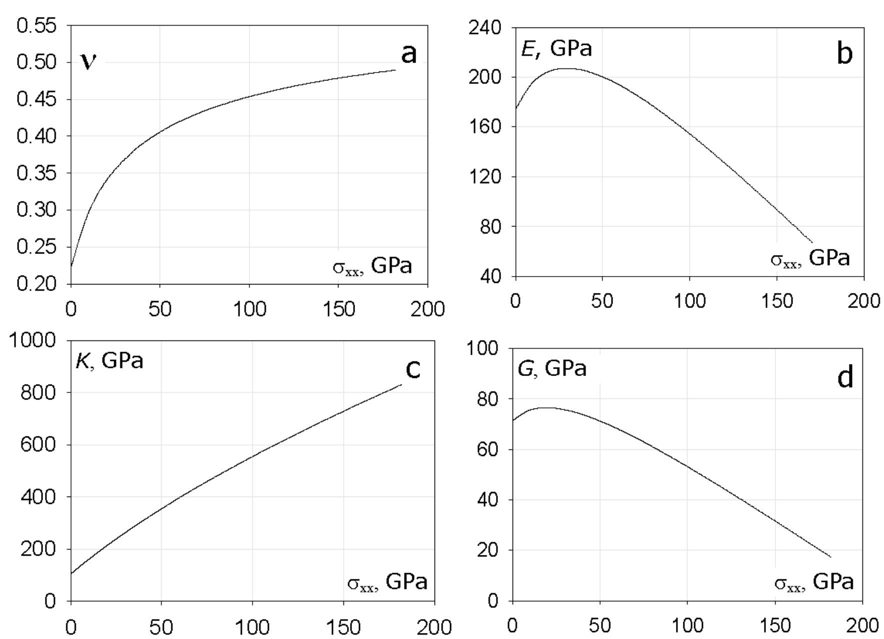


Fig. 4 –Poisson ratio (a), elasticity modulus (b), bulk modulus (c), and shear modulus (d) versus shock compression stress for uranium.

Conclusions

1 New data on longitudinal C_ℓ (σ_{xx}) and bulk C_B (σ_{xx},) sound velocities was obtained in the stress range $10 \le \sigma_{xx} \le 250$ GPa of single shock compression, measurements accuracy no less than ±3%.

2 The solid-liquid coexistence region for U was evaluated at $\sigma_{xx}^{\gamma-L}$ = 160-190 GPa.

3 General dependences of longitudinal C_ℓ and bulk C_B sound velocities on the U density behind the shock wave front were established within $0 \le \sigma_{xx} \le 160$ GPa (solid phase):
   - for longitudinal sound velocity C_ℓ (km/s) = 0.232×ρ (g/cm^3)−1.141;
   - for bulk sound velocity C_B (km/s) = 0.318×ρ (g/cm^3)−3.666.

4 Taking into account the experimental measurements at VNIIEF in 1979, the general dependence describing the variation of bulk C_B sound velocity on the U density behind the shock wave front was established within $190 \le \sigma_{xx} \le 320$ GPa (melt): C_B (km/s) = 0.269×ρ (g/cm^3)−2.316.

5 The obtained dependences of Poisson ratio ν, elasticity modulus E, bulk modulus K, and shear modulus G on the stress at the shock wave front within $0 \le \sigma_{xx} \le 160$ GPa – the region of shock compression of solid phases of uranium − will be used to verify elastic-plastic models.

Reference.

[1] E.A. Kozlov, in: Zababakhin Scientific Talks, edited by E.N. Avrorin and V.A. Simonenko, volume 849 of AIP Conference Proceedings, Melville, New-York (2006).

[2] M. Pénicaud, in: Shock Waves in Condensed Matter, edited by J.R. Asay, R.A. Graham, and G.K. Straub, Elsevier Science Publishers B.V. (1984).

[3] J.M. Wills, and Olle Eriksson, in: High-Pressure Science and Technology, edited by S.C. Schmidt, J.W. Shaner, G.A. Samara, and M. Ross, American Institute of Physics, New York (1994).

[4] J.M. Wills and Olle Eriksson, Phys. Rev. B 45,24,13879. (1992)

[5] P. Söderlind, Phys.Rev.B 66,085113. (2002)

[6] J. Akella, G.S. Smith, and H. Weed, J.Phys.Chem.Solids 46,3,399. (1985)

[7] J. Akella, G.S. Smith, R. Grover, Y. Wu, and S. Martin, High Pressure Research 2,295. (1990)

[8] J. Akella, S. Weir, J.M. Wills, and P. Söderlind, J.Phys.Condens.Matter 9,L549. (1997)

[9] C.S. Yoo, H. Cynn, and P. Söderlind, Phys.Rev.B 57,10359. (1998)

[10] T. Le Bihan, S. Heathman, and M. Idiri, Phys. Rev.B 67,134102. (2003)

[11] J. Viard, Colloques Internationaux, Gif-sur-Yvette, Paris (1962).

[12] L.V.Altshuler, A.A.Bakanova, M.I.Brazhnik, V.I.Zhuchikhin, S.B.Kromer, K.K.Krupnikov, and R.F.Trunin, Rus. J.Chem. Phys. 14,2-3,65 (1995)

[13] Los Alamos Series on Dynamic Material Properties, LANL SHOCK HUGONIOT DATA, edited by S.P.Marsh, University of California Press, Berkeley, Los Angeles, London (1980).

[14] Los Alamos SHOCK WAVE PROFILE DATA, edited by Charles E. Morris, University of California Press, Berkeley, Los Angeles, London (1982).

[15] A.L. Mikhailov et al. in: Advances in Material Science, Prague, Chech Republic (2009).

[16] E.A. Kozlov, B.V. Litvinov, V.K. Orlov et al. in: Shock Waves in Condensed Matter, St.-Petersburg, Russia (1994).

[17] A.B.Medvedev. Model of Equation of State of Metals Taking into Account Evaporation, Thermal Ionisation, and Melting. VANT. Series: Theor. and Appl. Phys., 1992, Issue 1, p.12

[18] I.V.Lomonosov. Phase Diagrams and Thermodynamic Properties of Metals at High Pressures. PhD thesis, Inst. Probl. Chem. Phys., Chernogolovka, 1999

[19] C. Dai, and H. Tan, J. Appl. Phys. 92,3,5019. (2002)

[20] R.G. McQueen, and J.M. Brown, J. of Geoph. Res. 91,B7,7485. (1986)

[21] R.G. McQueen, J.W. Hopson, and L.N. Fritz, Rev. Sci. Instr. 53,2,245. (1982)
[22] M.F.Gogulja, and I.M.Voskoboynikov, Rus. J. Phys. Comb.& Expl. 24,6,127. (1988)
[23] J.W. Shaner, R.S. Hixson, and D.A. Boness, in: Shock Waves in Condensed Matter, Elsevier Science Publisher, B.V. (1987).