ISSN 0018-151X, High Temperature, 2017, Vol. 55, No. 3, pp. 365–369. © Pleiades Publishing, Ltd., 2017.
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THERMOPHYSICAL PROPERTIES OF MATERIALS

Evaluation of Glycerol Viscosity through the Width of a Weak Shock Wave

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Received October 3, 2016

Abstract—Measurements of the width of a shock wave in glycerol dependent on the pressure of shock compression were taken to improve the method of determination of liquids viscosity. It was found that the time of growth of parameters in a shock wave decreases to the limit of time resolution of modern measurements, which is approximately 1 ns at the shock compression pressure of around 2.5 GPa. The values of viscosity, obtained at these parameters, are in agreement with experimental data. The transition to stepwise shock compression expands the pressure range, available for measurement by this method, and also makes possible the opportunity to vary the temperature.

DOI: 10.1134/S0018151X17030105

INTRODUCTION

The issue of the viscosity of liquids at high pressures and increased temperature arises during the analysis of various problems of geophysics, explosion physics, and high-velocity impact. In this series, the issue of viscosity of iron melts (and also the viscosity of their mixtures with nickel and some light elements) from which the outer core of the Earth consists, is of great importance [1]. There are few methods proposed for measuring the viscosity in the conditions of static compression [2] as well as for powerful shock waves [3–7]. The problem is in the fact that the pressure range, in which the measurements of viscosity in the conditions of hydrostatic pressure were performed, is limited by the value of a few GPa. Experiments with shock waves can be carried out in an unlimited pressure range, in principle, but the methods used to measure the viscosity are usually inapplicable for melted metals. Particularly, the methods based on measurements of acceleration of metal wires by the flow of shock-compressed liquid [4, 5], dopant ionic conductivity [6], and fluorescence attenuation [7] are applicable only for nonconductive liquids. The method consisting of the registration of attenuation of sinusoidal perturbations in the front of shock wave [3] is more universal; however, the results obtained using this technique contradict the data of other measurements, and they seem to be unreliable due to this fact. In this regard, the search and verification of more functional and reliable new ways of measuring the viscosity of shock-compressed liquid is of great importance. Moreover, the issue on which there is the possible dependence of viscosity of common liquid on the strain rate, is of importance. In this work, the possibility of shock wave use, propagated by the shock-compressed liquid, was estimated for these purposes by test experiments with glycerol and water.

It is known that shock waves have a finite width, controlled by the substance viscosity. The lower the viscosity, the shorter the time of compression of a substance in a shock wave. There is a relation between the velocity of compression in a shock wave $\dot{\varepsilon}_x = -\rho_0\, dV/dt = -(1/U_S)\, du/dx$ and coefficient of shear viscosity η is presented in a well-known monograph by Ya.B. Zel'dovich and Yu.P. Raizer [8]

$$-\frac{4}{3}\eta\frac{du}{dx} = \rho_0 U_S^2\left(1-\frac{V}{V_0}\right) - P. \tag{1}$$

The first part of relation (1) expresses the differences of compression stress σ_x on the Rayleigh line (σ_x is assumed as positive value during compression) and the pressure P at the same compression V/V_0. Here, U_S is the velocity of shock wave, V, V_0 are the current and incident value of specific volume; ρ, ρ_0 are the density of substance and the density of substance in an initial state; and u is the current value of particle velocity of substance in a shock wave. The difference between the normal stress and the pressure is the deviator component of stress, which is 4/3 of maximum shear stress τ in the conditions of uniaxial deformation of shock compression. Thus, to estimate the viscosity by the compression rate in a shock wave, we have

$$\eta = \tau/\dot{\varepsilon}_x. \tag{2}$$

To realize this method in practice, it is necessary to check its applicability on the example of any sample investigated previously, and that the measurements of the compression rate in the shock waves in glycerol and water are carried out.

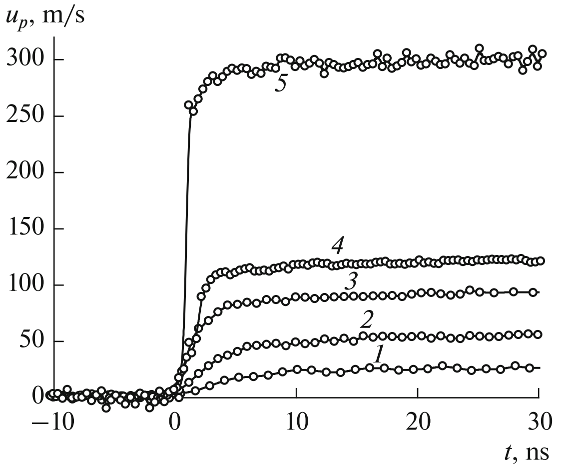

Fig. 1. Profiles of shock waves in glycerol, measured on the surface of contact with a window made of LiF or sapphire; the interval between the point of digital registration is 0.4, 0.8 or 1.2 ns; *1*—P_1 = 0.52 GPa (sapphire), *2*—0.46, *3*—0.77, *4*—1.0, *5*—2.5.

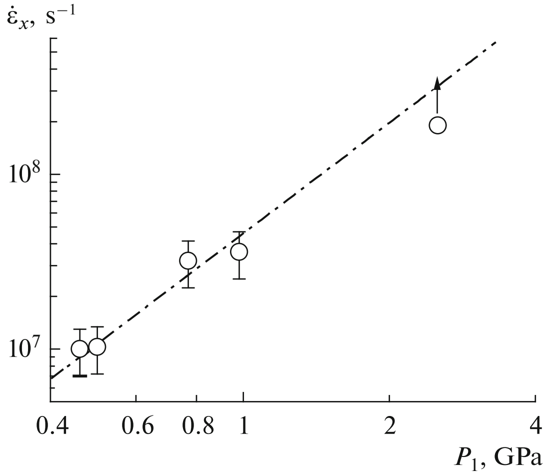

Fig. 2. Rate of compression in shock wave as a function of pressure of shock compression; the dot at P_1 = 2.5 GPa was obtained at the limit of the time resolution of the measurements is likely to be the lower bound.

EXPERIMENTAL

The experiments were carried out with pure grade glycerol at room temperature. Glycerol was poured into a sealed cuvette with a metallic bottom, through which the shock wave was introduced into the sample, and a window made of lithium fluoride or sapphire was used as a lid. The bottom was made of aluminum, copper, or molybdenum. The shock wave was created by impact of an aluminum or copper flyer plate at a speed ranging from 300 to 2600 m/s. The acceleration of a flyer plate with velocity at 300–350 m/s was performed using a ballistic facility, a "gas gun". Explosive devices were used for high-speed launching. The history of velocity of the window contact surface with sample $u_p(t)$ in the process of compression waves output was monitored with the use of a VISAR laser Doppler velocity meter [9]. To reflect the probing laser radiation of the VISAR device, a thin reflective layer of aluminum was deposited on the surface of the window facing the sample by vacuum deposition. The time resolution of measurements was approximately 1 ns at the used parameters of equipment.

RESULTS AND DISCUSSION

The profiles of shock waves $u_p(t)$ with the pressure of shock compression ranging from 0.46 to 2.5 GPa obtained in glycerol are shown in Fig. 1. The measured rise time of shock wave at a shock compression pressure of 2.5 GPa reaches the limit of temporal resolution of the technique. At lower pressures, the width of shock wave is completely measurable.

The results of measurements of maximum compression rate in shock wave $\dot{\varepsilon}_x$ dependent on the pressure of shock compression P_1 are presented in Fig. 2. The rate of compression was determined as $\dot{\varepsilon}_x = \dot{u}_p / U_S$, where $\dot{u}_p$ is the gradient of particle velocity, determined by the measured profile of $u_p(t)$, taking into account the difference of dynamic impedances of glycerol and material of the window. The Hugoniot of glycerol was used in the calculations based on reference data [10] as $U_S = 1.95 + 2.59u_p - 0.4u_p^2$; at $u_p < 0.5$ km/s the experimental data are better described by the linear equation $U_S = 1.9 + 2.71u_p$. As can be seen, the results of measurements of compression rate in a shock wave are well approximated by the power law with an exponent of 2.1

$$\dot{\varepsilon}_x = 4.6\times10^7 (P_1/P_0)^{2.1}. \qquad (3)$$

It is worth noting that the exponent for the solids in a similar relation is close to four [11]. Obviously, the difference is caused by the discrepancy in the nature of the viscosity of liquids and solids. For solids, internal friction is not linked with the momentum transfer at the random motion of molecules, rather it is linked with the dynamics of dislocations and motion of "other carriers of plastic deformation". In [12] the results of similar measurements at the pressure of a few hundreds MPa are described by the power law dependence with an exponent of 1.1. However, the time resolution in [12] was worse than the value used in this article due to the application of foil reflectors of probing radiation.

Figure 3 illustrates the results of the estimation of glycerol viscosity by the measured values of maximum compression rate in a shock wave. The evaluations were done based on Eq. (2) with the use of maximum values of τ and $\dot{\varepsilon}_x$. The maximum shear stress was determined by the deviation of the Rayleigh line from the Hugoniot in P–V coordinates. For the shock wave in a form of $U_S = c_0 + bu$ (c_0 is the velocity of sound, b is the Hugoniot slope), the deviation was expressed as

$$\rho_0 U_S^2\left(1-\frac{V}{V_0}\right)-P=\rho_0 U_S^2\varepsilon_x-\frac{\rho_0 c_0^2\varepsilon_x}{(1-b\varepsilon_x)^2}. \quad (4)$$

The data of articles [5, 6], obtained through analyzing a wire acceleration by the flow of liquid behind the shock wave and by the measurement of doped conductivity of shock compressed liquid, are presented in Fig. 3 [5, 6]. It is seen that the differences between the data are small, which indicated the small effect of strain rate (up to 10^8 s^{-1}) on the viscosity coefficient. The increase of temperature at the shock compression of a substance limits the viscosity growth with increasing pressure.

At the shock compression pressure of 2.5 GPa, the width of the shock wave in glycerol decreases to the limit of resolution of measurements, which makes impossible the measuring of viscosity by this method at higher pressures. The problem is solved by modifying the method with the transition to stepwise shock compression. In this case, the experiment was organized by allowing the weak shock wave to generate in a shock compressed substance, the width of which is already large enough to be measured and appropriate for viscosity determination. Such a stepwise shock compression can be arranged by placing the sample between plates made of materials with higher dynamic impedance or by the use of a thin intermediate base plate between the impactor and the sample made of material with lower or higher dynamic impedance than that of the sample and impactor. The first approach was used in this work. The profile of particle velocity, measured on the boundary between a 0.2-mm-thick glycerol layer and a sapphire window, is presented in Fig. 4. The shock wave was introduced into the sample through a copper base plate with high thickness. As a result of multiple reflections of shock wave in glycerol between the sapphire window and copper base plate, a pressure of 3.7 GPa was reached. The amplitude of each subsequent wave was less than the pressure rise on the previous step of compression, and the width was larger. At such statement, the compression process approaches the quasi-isentropic one, and the irreversible temperature growth is lowered.

Analysis of stepwise shock compression is usually performed based on the assumption of coincidence (or mirror symmetry) of Hugoniots for incident and reflecting waves and for Riemann isoentropes in pressure–particle velocity coordinates. The measurements show that the approximation for nonporous substance is accurate enough, if there are no physicochemical transformations in a process shock compression. In such a case for the second and subsequent shock waves, it is necessary to use the Lagrange velocity of sound in a shock compressed substance $a_0 = c_0 + 2bu$, or $a=\sqrt{c_0^2+\frac{4bP}{\rho_0}}$ in a linear relationship between the velocity of shock wave and particle velocity. The slope coefficient b_1 of second Hugoniot was found from the condition of its matching with the first Hugoniot in the coordinates particle velocity–pressure

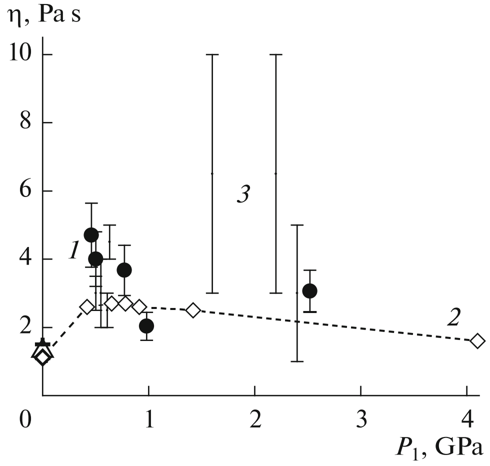

Fig. 3. Dependence of glycerol viscosity on the pressure of shock compression: *1*—data of this work, *2*—[6], *3*—[5].

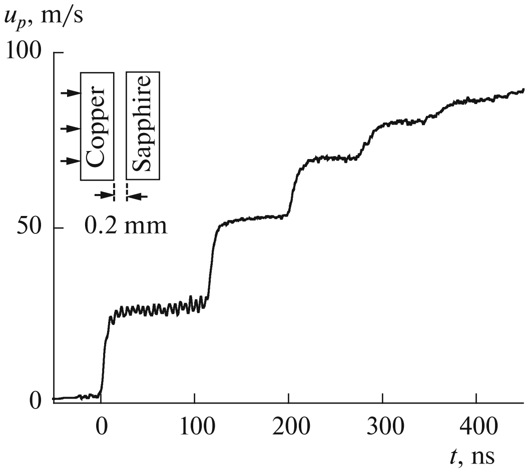

Fig. 4. Profile of particle velocity at the manifold reflections of shock wave in 0.2-mm layer of glycerol between sapphire window and copper base plate.

$$P/\rho_0 = c_0u_1 + bu_1^2 + (c_0 + 2bu_1) \times (u-u_1) + b_1(u-u_1)^2 = c_0u + bu^2, \quad (5)$$

from which $b_1 = b$ was obtained. The pressure–particle velocity diagram, used during analysis of stepwise compression in the experiment (Fig. 4), is shown in Fig. 5. The value of particle velocity behind the shock wave was recorded on the surface of sapphire window contact with glycerol (points B_i), while the parameters of shock waves passing to this surface correspond to points A_i on the Hugoniot of copper base plate. The parameters of shock wave recorded on the boundary with the window and the coefficients of corresponding Hugoniot were determined with the use of a diagram similar to that presented in Fig. 5. Then, the maxi-

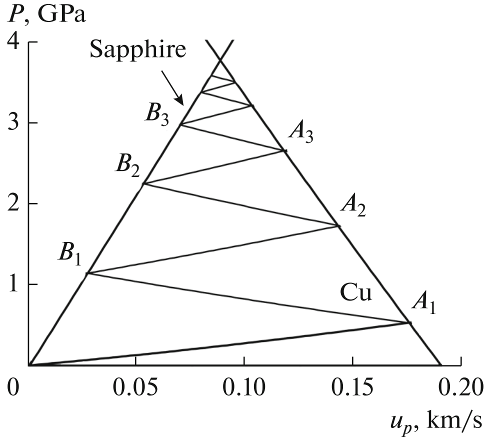

Fig. 5. Diagram of stepwise shock compression of glycerol in experiment, shown in Fig. 4.

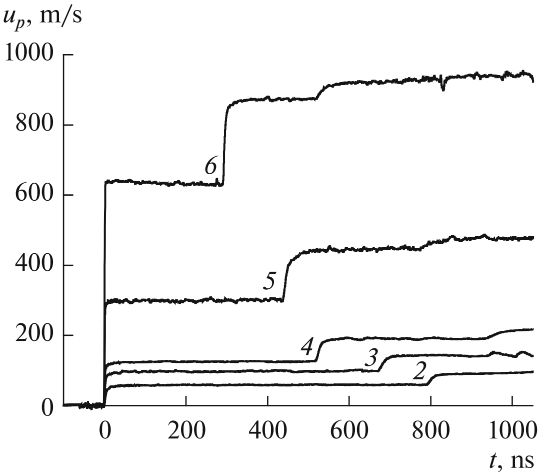

Fig. 6. The profiles of waves of stepwise shock compression of glycerol; (*2–6*) see the table.

mum value of shear stress was determined in accordance with Eq. (4) by the deviation of the Rayleigh line from the Hugoniot.

The next circumstance, which is necessary to take into account at the analysis of shock wave width, is the reaching of the steady regime of its propagation. Relations (1) and (4) are appropriate only for steady compression wave. It is intuitively clear that the steady waveform can be achieved after the wave passes a distance much larger than its width. According to Blend evaluations [11, 13], the steady shock wave is formed after its passing distance H, which is

$$H \approx \frac{8}{3}\frac{\delta}{b(\Delta u_p/U_S)}, \qquad (6)$$

where δ is the width of shock wave, and b is the Hugoniot slope in u_p–U_S coordinates. In the experiment, the results of which are shown in Fig. 4, the Lagrangian width of a shock wave, conventionally defined as $\delta = U_S\,\Delta u_p/\dot{u}_p$, increases from 17 μm for the first "stair" to 44 μm for the fourth and even more for the fifth. In other words, the first one to two shock waves can be treated as more or less sustainable at a distance of 0.2 mm in this experiment.

Further measurements were carried out at a thickness of glycerol layer above 1 mm. The parameters of the experiments are presented in the table (the indexes correspond to number of stairs). The profiles of particle velocity at the stepwise shock compression of glycerol are shown in Fig. 6. It is seen, even at the used scale, that the width of the second and subsequent stairs is higher than the width of the first shock wave, which makes possible their application for estimation. Attention is drawn to the dissymmetry of shock waves representing the sharp initial segment, behind which the area of slow growth follows. Probably, it is linked with the increase of viscosity coefficient with pressure growth.

The evaluations of glycerol viscosity in the conditions of stepwise shock compression are given in Fig. 7 and in the table. The pressure values correspond to the state behind the shock wave, although it would be correct to take the pressure in the middle of the shock wave, because the compression velocity and shear stress were determined specifically for it. Time of compression in the first shock wave with pressure higher than ~2 GPa becomes less than 1 ns; for these experiments, the viscosity values in the first shock wave were taken from the reference data [6] based on

Experimental conditions and estimates of the glycerol viscosity under the conditions of stepwise shock compression

No.	Material of base plate	Sample thickness, mm	Material of window	P_1, GPa	η_1, Pa s	P_2, GPa	η_2, Pa s	P_3, GPa	η_3, Pa s
1	Cu	0.20	Sapphire	0.52	4.0	1.7	6.4	–	–
2	Al	1.25	LiF	0.46	4.7	1.2	7.4	1.5	6.9
3	Al	1.26	LiF	0.77	3.7	1.7	4.8	–	–
4	Cu	1.05	LiF	1.0	2.0	2.4	6.4	3.0	8.2
5	Cu	1.33	LiF	2.5	3.1	5.9	16.9	6.9	16.9
6	Mo	1.28	LiF	–	–	13.7	13.3	15.7	14.7

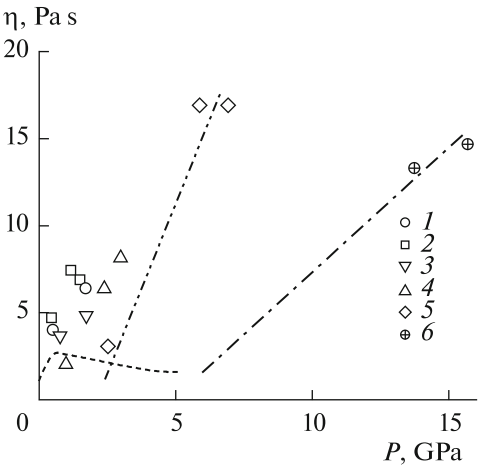

Fig. 7. Evaluations of glycerol viscosity in the conditions of stepwise shock compression: *1–6* see the table; dotted line—data [6], dash-dot lines connect the dots, obtained in one experiment.

the measurements of doped electrical conductivity. The range of pressures, for which it was possible to measure the viscosity by the width of shock wave, expanded from 2–2.5 GPa to 15 GPa. It is known that the viscosity of glycerol at constant temperature grows with pressure, but it rapidly decreases during heating. Since the increment of temperature at the stepwise compression is lower than for a single compression, it is natural that the drop of viscosity changes to its growth with the transition to stepwise compression in the process of pressure increase.

The viscosity of water is three orders the magnitude lower than the viscosity of glycerol at normal conditions. Correspondingly, in all experiments with water in the formulation described above, the time of parameters growth and in the first, and subsequent, shock waves was on the limit of time resolution of measurements. Although, the value of water viscosity was not obtained, the result can be treated as the confirmation of correctness of this method.

CONCLUSIONS

The experiments performed with water and glycerol confirmed the possibility of the application of the method for measuring the viscosity of liquids usning rise time of parameters in a shock wave. The width of shock wave in glycerol decreases fast with the increase in pressure of shock compression, and it is less than 1 ns at a pressure of 2.5 GPa. The viscosity of glycerol drops because the pressure growth of shock compression is conjugated with a temperature increase. The transition to stepwise shock compression, proposed in this work, expands the pressure range, available for measurements of this method, and it gives a possibility to also vary the temperature. The ratio of viscosities of glycerol and water remains in the conditions of shock compression. This method can be applied to metals, provided that the shock waves of relatively low amplitude will be generated to measure viscosity in dynamically compressed substance. The advantage of the method is the fact that it is practically direct; there are only conservation laws and the equation of the state of the investigated substance used for interpretation of measurement results. This is the difference of this method, for example, in comparison to the standard method of torsional vibrations, the application of which is linked with the analysis of numerous sources of error [14].

ACKNOWLEDGMENTS

This study was supported by the Russian Science Foundation grant, project no. 14-50-00124.

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Translated by A. Bannov