

# Experimental study of mechanical properties of liquids under shock wave loading

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**Abstract.** Glycerol and silicone oil were studied experimentally under shock-wave loading conditions at different temperatures and strain rates. It was found that the temperature has a significant influence on the spall strength of glycerol near the point of phase transition and weak influence on the spall strength of silicone oil. The spall strength of the silicone oil does not depend on the strain rate also. Dynamic viscosity of glycerol measured at the wave front found to be strain rate sensitive.

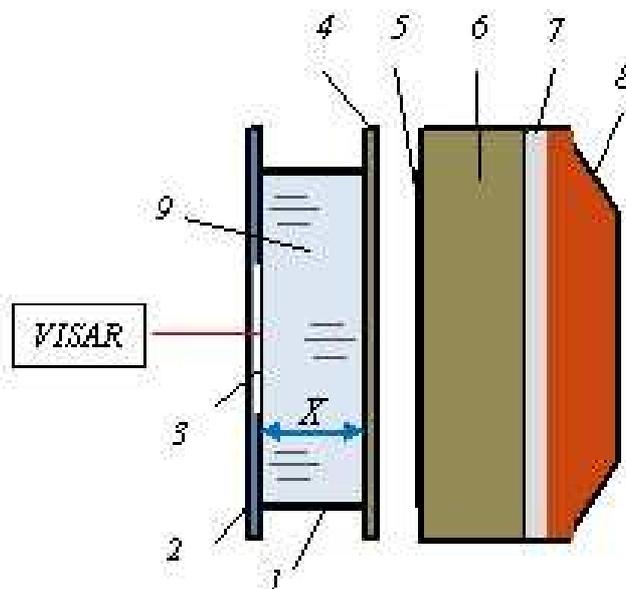
## 1. Introduction

The strain rate dependence of the spall strength of liquids near the melting point is most pronounced. The most illustrative example are the data obtained from water experiments: at 20 °C, the spall strength  $P_s$  is practically independent of the strain rate  $\dot{\epsilon}$  ( $0.3 \times 10^5$ – $1.4 \times 10^5$  s<sup>-1</sup>) [1], whereas at 0.7 °C,  $P_s$  is a power function of  $\dot{\epsilon}$  ( $1.8 \times 10^5$ – $5.2 \times 10^5$  s<sup>-1</sup>) [2]. It is well known that glycerol remains in the liquid state far below the melting point and in order to obtain glycerol in the crystalline state the nucleus of crystallization should be obtained, whose velocity of creation is the greatest at a temperature about 70 K below the melting temperature of the crystalline glycerol. So it is possible to investigate spall strength of the supercooled glycerol. In this work, in order to clarify the nature of this phenomenon we performed a series of experiments allowing us to determine the spall strength of glycerol over a wide range of strain rates and different initial temperatures near the phase transition point. The silicone oil was used as a reference liquid, the freezing point of which is well below the test temperature.

## 2. The experimental technique

The scheme of experimental setup is shown in figure 1. A cell with a liquid represented a metal ring-shaped cuvette 1 (filling hole was at the top of the cell) of height  $X$  (hereinafter “sample thickness” or “thickness  $X$ ”). On the one side the cuvette was bounded by a plate 2 in the center of which there was a hole of diameter 16 mm covered with aluminum foil 3 of thickness 7  $\mu$ m, and on the other side it was bounded by screen 4. The plane shock wave, which was generated in attenuator 6 by conical explosive lenses 7, 8 [3], accelerated an aluminum projectile 5. After collision of thin projectile 5 with screen 4 the compression pulse penetrated into the test





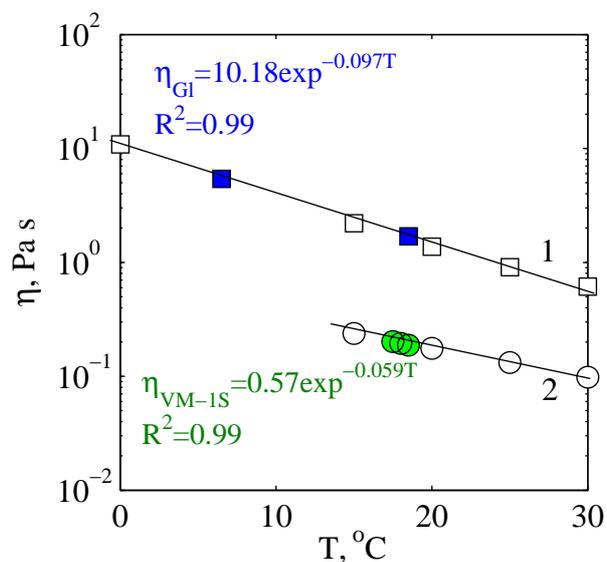
**Figure 1.** The experimental scheme [1]. See table 1. The interference optical system VISAR for registration of the free-surface velocity profiles in liquids.

**Table 1.** The explanatory table for figure 1.

		Thickness, mm	Diameter, mm
1	Ring, Steel	$X = 2-20$	from 50
2	Window, PMMA	2	70
3	Reflector, Al	0.007	2.6
4	Screen, PMMA	2	70
5	Projectile, Al	0.4	50
6	Attenuator, Steel3	20	120
7	Guide lens	—	—
8	Explosive substance	—	—
9	Liquid for test (see. table 2)	—	—

liquid 9. Loading conditions were varied by changing the thickness of the liquid layer  $X$ . The VISAR was used to register the free surface velocity [1,4]. The laser beam was reflected from the aluminum foil 3, which separate the liquid from the air. The geometrical dimensions of the cell (the cell diameter was much greater than the height of the cell) provides the one-dimensional loading conditions and impeded the arrival of the lateral (from the wall of the cell) unloading wave during the whole period of process recording. Table 1 shows the main parameters of the experimental setup.

Research were carried out on the technical glycerol (GOST 6824-96) and vacuum silicone oil VM-1S. The diagram (figure 2) shows the power law dependence of the dynamic viscosity of two liquids on temperature (white markers correspond to data obtained with the use of viscometer



**Figure 2.** Dynamic viscosity as a function of temperature. Colored markers are the data obtained by the approximation formulas.

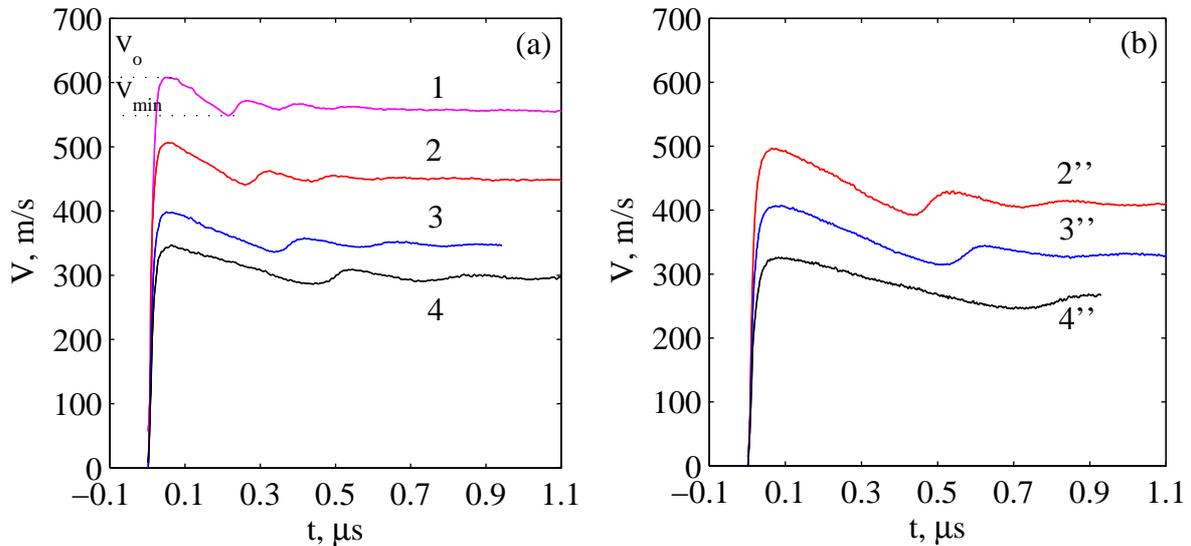
**Table 2.** Rheological parameters of liquids.

	Density, $\text{kg}\cdot\text{m}^{-3}$	Sound speed, $\text{m}\cdot\text{s}^{-1}$	Viscosity, Pa s
Glycerol	1260	1796	1.69 (18.5 °C), 5.42 (6.5 °C)
VM-1S	863	1392	0.194 (18 °C)

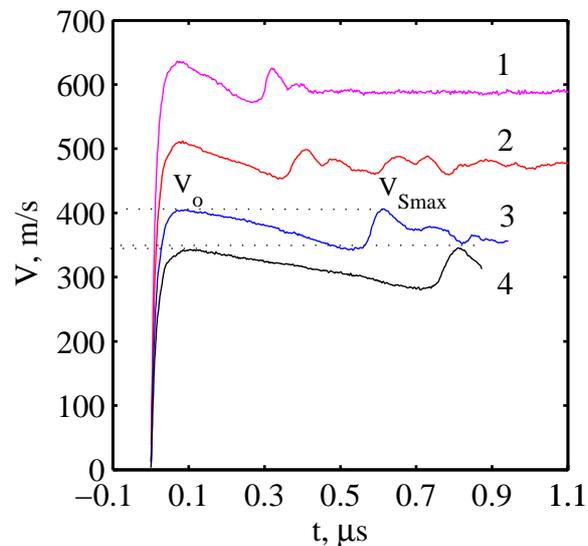
to an accuracy of 0.001 Pa s). Table 2 presents the rheological properties of liquids. The vacuum silicone oil is characterized by a small change in viscosity at significant changes of temperature and low surface tension  $\sigma$ , whereas the viscosity of glycerol essentially depends on temperature  $T$ , and the value of  $\sigma$  of glycerol equaling 0.070 Pa·m is close to the value of  $\sigma$  for water equaling 0.074 Pa·m. It should be noted that the glycerol tests were performed at temperatures of 18.5 °C and 6.5 °C, which are equal to or below the melting point of 18.5 °C. At the same time, the temperature of the experiment with silicon oil experiments (18 °C) was much higher than the melting point of oil, which is lower than minus 50 °C.

### 3. Results and discussion. Rheology of liquids

The dependencies of the free surface velocity on time, obtained with the aid of VISAR are shown in figures 3a, 3b and 4. In the experiments we used thin projectiles, so the interaction of the incident rarefaction wave with a shock wave led to the formation of triangular compression pulse. Its emergence on the free surface causes an abrupt increase in the velocity of the surface to the value  $V_0$  followed by its reduction. The centered rarefaction wave propagating deep into the liquid, interacts with the incident rarefaction wave, which leads to negative pressures and internal rupture—spalling. In the process of fracture the tensile stresses relax to zero, forming a compression wave, which penetrates the free surface in the form of spall pulse. The subsequent velocity fluctuations are caused by the circulation of waves in the spall plate. The magnitude



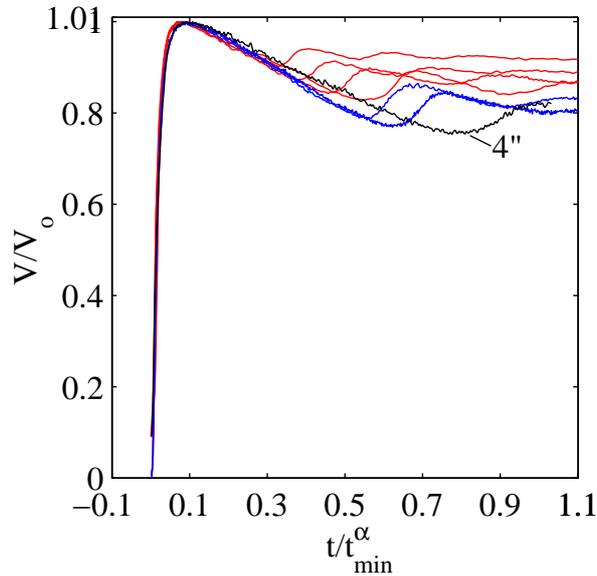
**Figure 3.** Free surface velocity profiles obtained for glycerol at different thicknesses  $X$ : a—at initial temperature 18.5 °C: 1—2 mm; 2—4 mm; 3—8 mm; 4—12 mm. b—at initial temperature 6.5 °C: 2''—4 mm; 3''—8 mm; 4''—12 mm.



**Figure 4.** Free surface velocity profiles obtained at different thicknesses  $X$  of VM-1S at initial temperature 18 °C: 1—2 mm; 2—4 mm; 3—8 mm; 4—12 mm

of the negative pressure  $P_s$  is determined by the difference between the maximum velocity of the free surface  $V_o$  and velocity  $V_{\min}$  reached at the time of spall pulse release [1–3, 5]. The experiment results demonstrate good reproducibility from one test to another.

In the experiments with vacuum silicone oil the free surface velocity profiles are different from that of the glycerol (figure 4). Firstly, the spall pulse has a much steeper front. The fact that the slope of the front is determined by the kinetics of pore growth [6] allow us to assert that the rate of pore formation in the glycerol is less than in silicone oil. It should also be noted that the

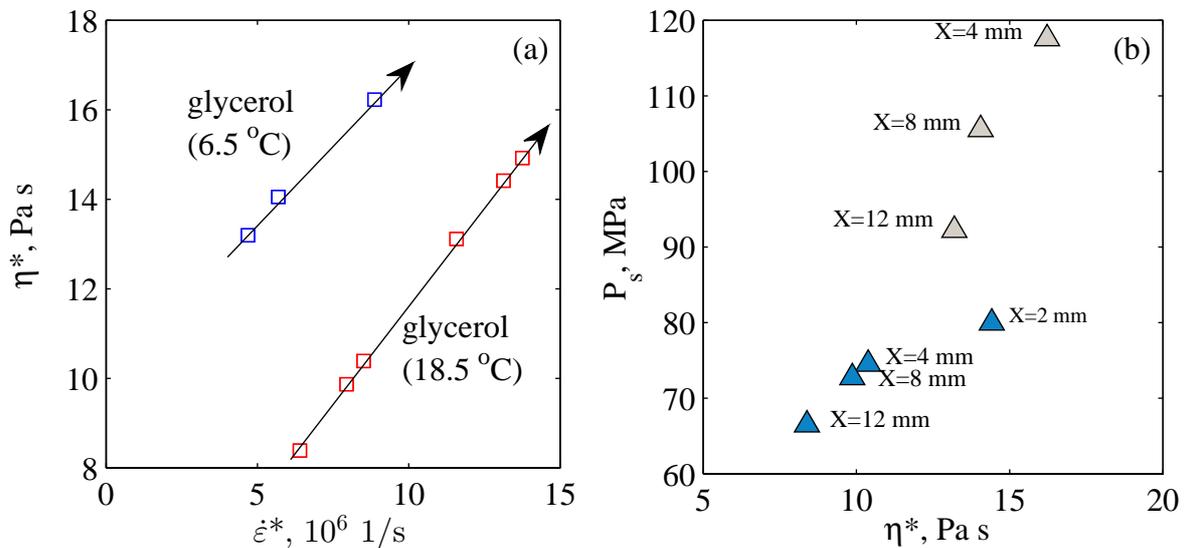


**Figure 5.** Free-surface velocity profiles (figure 3) plotted in dimensionless coordinates. Data for glycerol.  $\alpha$  is exponent in power law of the spall strength  $P_s$  depend on strain rate  $\dot{\epsilon}$ .

amplitude of the spall pulse in the oil almost coincides with (figure 4, profile 4), and in some cases even exceeds the amplitude of the incident pulse (figure 4, profile 3). Similar behavior of spall pulse amplitude was observed in the experiments of the plane shock wave in water [1], and in the experiments of the shock wave initiated by electrical wire explosion (EEW) [5]. This phenomenon is due to the growth of pores in the medium under compressive stress, which is a consequence of the inertial expansion of bubbles caused by a change of the pressure sign [7]. Secondly, almost all the velocity profiles in the silicone oil display velocity fluctuations behind the spall pulse front, the period of which is significantly less than the time of wave circulation in the spall plate. This is probably due to a fracture inside the spall plate, leading to its division to thinner spall layers.

The obtained free-surface velocity profiles allows us to define the values of the spall strength  $P_s$ , a strain rate  $\dot{\epsilon}$  in the unloading part of the pulse, the amplitude of the compression pulse  $P_o$  and the strain rate  $\dot{\epsilon}^*$  at the front of the compression wave (linear part). Processing of the free surface velocity profiles of glycerol shows that a decrease of temperature from 18.5 to 6.5 °C reduces the compression pulse amplitude  $P_o$  by 1.02 times the same impact velocity. A decrease in temperature led to a fall of the velocity minimum  $V_{\min}$  occurred before the onset of the spall pulse (figure 3b, profiles of 2'', 3'' and 4''), and thus to an increase value of the spall strength  $P_s$ . Spall strength of glycerol increases (from 46 MPa to 80 MPa at a temperature of 18.5 °C and from 92 MPa to 118 MPa at a temperature of 6.5 °C) with increasing strain rate from  $10^4$  to  $10^5$  s $^{-1}$ . A similar dependence  $P_s(\dot{\epsilon})$  was found in glycerol at a temperature of 19 °C in [2,8], in water near the freezing point (0.7 °C) [1] in the same range of strain rates, and in water at 20 °C [5] (from  $10^3$  to  $10^4$  s $^{-1}$ ). A decrease of glycerol temperature from 18.5° to 6.5 °C resulted in a 1.5-fold increase of the spall strength. A similar behaviour of  $P_s(T)$  obtained for glycerol [9] in the temperature range from minus 53° to 77 °C and strain rates of  $10^5$  s $^{-1}$ , is explained by the theory of homogeneous nucleation [9], developed in a more recent work by [7,8].

Unlike glycerol, spall strength  $P_s$  of silicone oil (about 37.9 MPa) is independent of the strain rate  $\dot{\epsilon}$  (from  $0.3 \times 10^5$  to  $1.3 \times 10^5$  s $^{-1}$ ). Similar results were obtained in the experiments with hexane [8], ethanol [10] and water at a temperature of 20 °C [1]. Such a weak dependence of the



**Figure 6.** Variation of dynamic viscosity with increasing strain rate (a). The influence of dynamic viscosity on the spall strength of glycerol (b). Black triangles correspond to glycerol data at the initial temperature 18.5 °C, white triangles correspond to glycerol data at the initial temperature 6.5 °C.

negative pressures on the strain rate can be explained using the model of on the assumption that viscosity of the fluid is constant. The last assumption is valid in the vicinity of 20 °C (figure 2).

For all examined liquids under shock wave loading the exponent  $\beta$  of the dependence  $\dot{\epsilon}^* = AP_o^\beta$  was less than 2: in glycerol at 18.5 °C  $\beta = 1.1$ , in glycerol at 6.5 °C  $\beta = 1.5$ , in the silicone oil  $\beta = 0.92$  in contrast to distilled water [5] where the value of the exponent  $\beta$  was about 3.2. Self-similarity of wave profiles for glycerol can be illustrated by figure 5 where free surface velocities are plotted in non-dimensional coordinates. The way for determining the dynamic viscosity of fluids (glycerol, water) during loading using formula is described in work [11, 12]:

$$\eta^* = \frac{3S(\dot{\epsilon}^*)^{\beta/2-1}}{4c_o^2\rho_o(A)^{\beta/2}}. \quad (1)$$

Here  $S$  is the value of the slope of the shock adiabatic curve, coefficients  $A$  and  $\beta$  are taken from the expression  $\dot{\epsilon}^* = AP_o^\beta$ ,  $c_o$  is the speed of sound in the liquid and  $\rho_o$  is the density of the liquid at 20 °C. Figure 6a shows the dependence of glycerol viscosity on the strain rate. Unlike water, the dynamic viscosity of glycerol increases with increasing strain rate  $\dot{\epsilon}^*$ , and both liquids behaved like pseudoplastic non-Newtonian fluids. We could not estimated viscosity of the silicone oil, because the coefficients of Hugoniot adiabat is still unknown. A quantified effect of viscosity on the spall strength is shown in figure 6b.

#### 4. Conclusion

These results show a strong influence of strain rate in the range of  $10^4$ – $10^5$  s<sup>-1</sup> on the spall strength of liquids near the melting temperature and the absence of such an effect, if the temperature of the experiments is significantly higher the melting point. The dynamic viscosity of glycerol increased with increasing strain rate, and the value of viscosity has a significant role in the spall strength of the material.

## Acknowledgments

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