A fiber-array probe technique for measuring the viscosity of a substance under shock compression*

Feng Li-Peng(冯立鹏), Liu Fu-Sheng(刘福生)†, Ma Xiao-Juan(马小娟), Zhao Bei-Jing(赵北京), Zhang Ning-Chao(张宁超), Wang Wen-Peng(王文鹏), and Hao Bin-Bin(郝斌斌)

Laboratory of High Temperature and High Pressure Physics, Southwest Jiaotong University, Chengdu 610031, *China*

(Received 13 January 2013; revised manuscript received 22 March 2013)

A fiber-array probe is designed to measure the damping behavior of a small perturbed shock wave in an opaque substance, by which the effective viscosity of substance under the condition of high temperature and high pressure can be constrained according to the flyer-impact technique. It shows that the measurement precision of the shock arrival time by using this technique is within 2 ns. To easily compare with the results given by electrical pin technique, the newly developed method is used to investigate the effective viscosity of aluminum (Al). The shear viscosity coefficient of Al is determined to be 1700 Pa·s at 71 GPa with a strain rate of 3.6×10^6 s^{-1}, which is in good agreement with the results of other methods. The advantage of the new technique over the electrical pin one is that it is applicable for studying the non-conductive substances.

Keywords: shock wave, viscosity coefficient, fiber array, high temperatures and high pressures

PACS: 83.85.Jn, 62.50.–p, 66.20.–d, 42.15.–i **DOI:** 10.1088/1674-1056/22/10/108301

1. Introduction

The viscosity coefficient is one of the important transport properties of fluids, but it is difficult to be determined experimentally at high temperatures and high pressures.[1–3] No doubt, to develop new technique to measure the viscosity of some relevant substances under such an extreme condition is a meaningful work.

For the melts at temperature below 2000 K and pressure lower than 10 GPa, the so-called falling sphere method[4–6] was used to measure the shear viscosity coefficient under static high-pressure conditions. For the higher pressures and higher temperatures, the small-perturbation oscillatory damping method, which is based on the time evolution of small perturbations in the front of a shock wave propagating in the investigated substance, is considered as an effective way to directly study the shear viscosity of shocked materials. In 1965, Sakharov *et al.*[7] designed a setup to measure the development of small perturbations in the shock front. However, only one experimental data point at 31 GPa has been reported so far, and some problems should be validated.[1] For simplifying the above experiment and testing the experimental result, Liu *et al.*[8] proposed a new experimental technique, known as the flyer-impact technique, and determined the shear viscosity coefficient of shock-compressed Al and Fe in a pressure range of 42 GPa–159 GPa.[8–13]

The flyer-impact technique mainly consists of two steps. One is to generate the shock wave with a small perturbed front, for which two-stage light-gas gun is used to accelerate a planar flyer to impact the sinusoidally grooved surface of the wedge-shaped sample. The other is to measure the oscillatory damping process of the perturbation amplitude of the shock wave propagating in the sample by electric pins. It is clear that this experiment cannot be used to directly measure the nonmetallic material because the sample itself is a part of the electrical circuit. Thus in this paper we suggest a fiber-array probe technique to improve the flyer-impact technique applicable to a greater variety of materials including insulators.

2. Flyer-impact experiment: Generating small-perturbed sinusoidal shock wave

The scheme of the flyer-impact technique is shown in Fig. 1, based on the oscillation damping method.[8] The flyer is planar, which is glued to the front of the projectile launched by a two-stage light-gas gun with a barrel of 25-mm inner diameter. There are some sinusoidal grooves on the impacted surface of the wedged sample. Aluminum is chosen because there are more measurement data available to make comparison. When the high-speed planar flyer impacts the crests of grooves on the sample surface, two shock waves are formed. One goes back into the flyer and the other goes forward into the sample, the latter will be studied in our experiments. Because the velocity of shock wave in sample is higher than the speed of flyer, a shock wave with geometrical disturbance on its front will be generated, when the flyer touches the troughs of the grooves (i.e., when the air gap between flyer and sample is completely closed). According to our fluid hydrodynamic simulation for

*Project supported by the National Natural Science Foundation of China (Grant Nos. 10974160 and 11002120) and the Fundamental Research Funds for the Central Universities (Grant No. SWJTU12CX085).

†Corresponding author. E-mail: fusheng_l@sohu.com

© 2013 Chinese Physical Society and IOP Publishing Ltd

the process of the gap closure, the initially disturbed shock wave has an approximate sinusoidal shape if the geometrical ratio (= depth/width) of the groove on the impacted surface is no more than 0.1). Both the initial position of the disturbed shock wave and the initial amplitude of the disturbance are important for describing the consequent damping behavior of shock front, because the disturbed shock wave will start its oscillation damping process which is governed by the viscosity of the sample. That is to say, if we know the evolution of the disturbed shock wave in the sample, its viscosity should be deduced. Also the propagation distance of shock wave in the sample is defined as damping distance (x) away from its initial position. Thus the next key step is to measure the oscillation damping process of the perturbation amplitude.

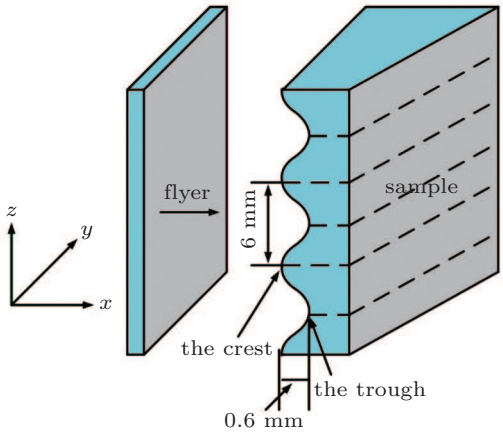


Fig. 1. (color online) Systematic diagram of producing small-perturbed sinusoidal shock wave.

3. Flyer-impact experiment: Measuring the evolution of the disturbed shock front

The wedged sample makes it possible to find how the small perturbed shock front evolutes with time. In the present work the fiber-array probe technique shown in Fig. 2 is designed. It detects the arrival times of shock wave at the back surface of wedged sample by capturing the light glowing from the air-gap between the sample and the polymethyl methacrylate (PMMA). There are three key points in this measurement.

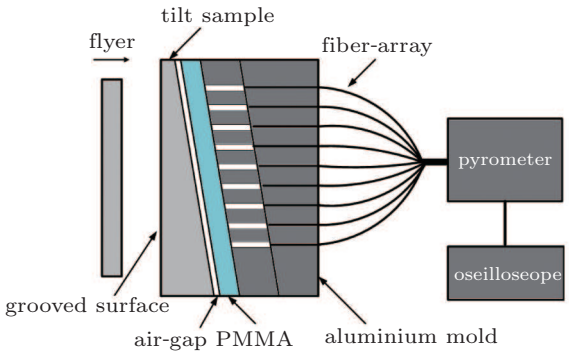


Fig. 2. (color online) Systematic diagram of the fiber array probe technique.

(i) Positioning of the fiber-array probe. Four groups of fibers are located at the positions corresponding to the crests and troughs of the impact surface with grooves in order to determine the amplitude of perturbation. When the shock wave arrives at the air-gap, full of air of 1 bar (1 bar = 10^5 Pa), the air will be multiply compressed and its pressure and temperature suddenly rise, and then a strong radiation will be generated.[14] Then the optical signal is detected by using the fiber-array probe, and converted into electrical signal by the pyrometer of multichannel, and transmitted to the oscilloscope. It is worth noting that the signals from the fiber probes in a group slanting along the direction of the sample are collected to a single channel of oscilloscope. Thus forty signals will be recorded by only four channels of oscilloscope.

(ii) Distinguishing the signals of the fiber probes. The PMMA is sandwiched between the sample and the fiber stand, so the PMMA acts as a light switch,[14] because it will quickly become opaque under shock compression of pressures above 15 GPa. The fiber probe receives the optical signal when the shock wave arrives at the air-gap between the sample and the PMMA. So it will generate an optical pulse with tens of nanosecond width, which is recorded by an electrical pulse. Therefore, the signals of the fiber probe can be distinguished one by one.

(iii) Improving the measurement accuracy. For this purpose, the effective way is to restrict the angular aperture of the fiber probe as much as possible, which can minimize the measurement area. However, the light intensity entering into the fiber should be large enough at the same time. Thus all fiber probes each with 250 μm in diameter are precisely positioned in an aluminum mold, and a distance of 20 mm is kept between the fiber head and the surface of the mold nearby the PMMA.

4. Experimental results and discussion

In our experiments the geometry of the sample of copper (Cu) is shown in Fig. 1. According to the size of flyer (24 mm) and the lateral wave propagation angle in aluminum at 71 GPa (about 40°),[15] the probe can be fixed in the area to avoid the effect of lateral wave. The speed of the copper flyer is 4.21 km/s, which is measured by an electromagnetic induction technique.[16] The shock pressures are calculated from the impedance-matching method,[14] in which the initial densities of aluminum and copper ρ_0 are 2.718 g/cm^3 and 8.93 g/cm^3, respectively. The Hugoniot parameters C_0 and s in the linear relation between shock and particle velocity are, respectively, 5.392 km/s and 1.34 for aluminum, and 4.2 km/s and 1.41 for copper.[15] So the shock pressure in our experiments is about 71 GPa.

The typical signals are recorded by Tektronix TDS684C oscilloscopes as shown in Fig. 3. The arrival times of the shock wave at the air-gap are easily read out by the peak positions of

light glowing signals. Its uncertainty is estimated to be within 2 ns. The shape of perturbed shock front and its development with damping distance are approximately mapped out by simply fitting the points corresponding to the same thickness with sinusoidal trend curves as shown in Fig. 4. The exact shape of the shock front could not be plotted only by the four scattered data points of arrival times, but our fluid hydrodynamic simulations of the disturbance and its development show that the geometrical shape of the shock front is approximately sinusoidal. Consequently, the behaviors of damping and oscillation of the perturbation amplitude can be figured out because the most important points of maximum and minimum on the sinusoidal shock front are pinned out. It has an oscillation damping characteristic as shown in Fig. 4. It is clear that the perturbation amplitude on the shock front experiences a decaying process until to zero point, then it rises to a maximum but in reverse phase, and then it decays again. Therefore, the evolution of the perturbation amplitude of the shock front with the damping distance can be obtained. For deducing the viscosity of aluminum from the measure data, we should know the initial amplitude of the shock front.

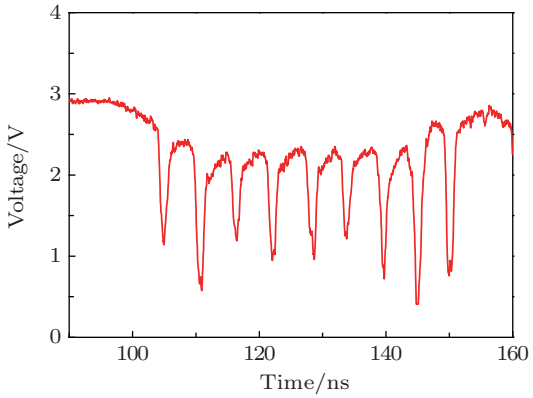


Fig. 3. (color online) Typical experimental signal at 71 GPa.

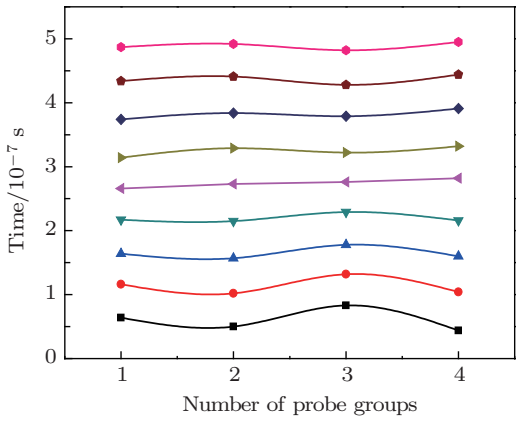


Fig. 4. (color online) Arrival times of the shock wave at detected positions of different fibers.

As pointed above, the beginning instant is the moment when the gap is completely closed. The initial amplitude (a_0) is defined as the half of the propagating distance of shock front in sample at the position of the crest of groove, i.e. $a_0 = (D-W)h/2W$, where h is the depth of groove, W and D are the velocity of the flyer and the shock wave respectively.

Therefore the evolution of the shock front can be described by the oscillation damping curve defined by the relative amplitude (i.e., a/a_0, the ratio of the disturbed amplitude a to the initial amplitude a_0) and the relative distance (i.e., x/λ, the ratio between the damping distance x of the shock front starting from its initial position and the wavelength λ of the sinusoidal disturbance). It is shown in Fig. 5.

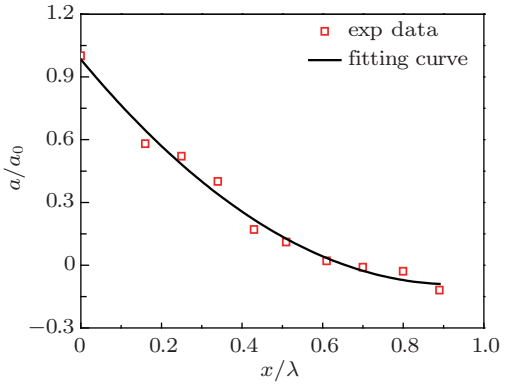


Fig. 5. (color online) Oscillation damping curve of perturbed shock wave.

To obtain the effective viscosity coefficients from the oscillation damping curve, it is necessary to numerically solve two-dimensional hydrodynamic equations of Eulerian form for viscous flow. We developed a finite difference scheme to slove the shock wave flow in viscous fluid, and the details were published elsewhere.[13] According to the specific condition of our flyer-impact experiment, we performed a two-dimensional viscous flow simulation, and obtained its numerical solution, which reveals the quantitative relationship between the viscosity coefficient and the oscillation damping curve.

Taking into account the position of the first zero-amplitude point of oscillation damping curve is sensitive to the shear viscosity coefficient of fluid, the dependence of the phase of zero-amplitude point (i.e., the value of the relative distance at first position) on shear viscosity coefficient is plotted in Fig. 6, which is the theoretical foundation for us to make experimental data analysis.

The measured oscillation damping curve indicates that the phase at zero-amplitude point is about 0.64 as shown in Fig. 5. The quantitative relationship between the relative distance and viscosity coefficient of aluminum at 71 GPa is shown in Fig. 6. The zero-amplitude point will delay with the viscosity coefficient rising. Combining Fig. 5 with Fig. 6 we obtain the effective shear viscosity coefficient of aluminum at 71 GPa to be close to (1700±100) Pa·s.

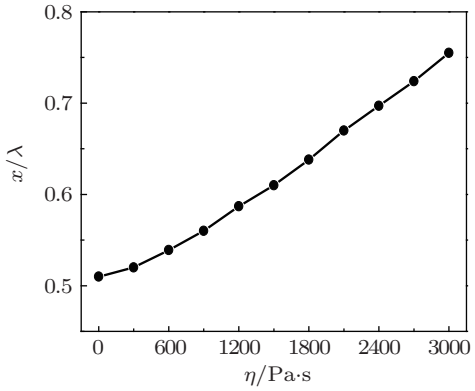


Fig. 6. Effects of viscosity on the phase of zero-amplitude point.

5. Summary

In this paper, we present a fiber-array probe technique for measuring the damping behavior of the disturbed shock front based on the flyer-impact technique. The damping and oscillation of the perturbation amplitude of the shock front in aluminum sample are observed, and then an oscillation damping curve is obtained. Using the quantitative relationship between the phase of zero-amplitude point and the shear viscosity coefficient, the shear viscosity coefficient of Al is determined to be 1700 Pa·s at 71 GPa. At 78 GPa the result given by electrical pin technique is 2800 Pa·s.[11] It is clear that the result in the paper is less than that obtained with the electrical pin technique. The difference in viscosity coefficient results from two factors. One is pressure, because the pressure is varying and the viscosity coefficient increases with shock pressure increasing;[11] the other is the time delay of light flashing during multiply compressing the air-gap.

Because the fiber-array probe technique is based on the light flash of an air-gap, it is independent of the conductivity of sample. So, the fiber-array probe technique is applicable to a greater variety of materials, especially to substances deep in the Earth.

References

[1] Miller G H and Ahrens T J 1991 *Rev. Mod. Phys.* **63** 919
[2] Mineev V N and Funtikov A I 2004 *Phys. Usp.* **47** 671
[3] Bi Y, Tan H and Jing F Q 2002 *Chin. Phys. Lett.* **19** 243
[4] Rutter M D, Secco R A and Liu H J 2002 *Phys. Rev. B* **66** 536
[5] Grady D E 1981 *Appl. Phys. Lett.* **38** 825
[6] Kushiro I 1976 *Geophys. Res.* **81** 6347
[7] Sakharov A D, Zaidel R M, Mineev V N and Oleinik A G 1965 *Sov. Phys. Doklady* **9** 1091
[8] Liu F S, Yang M X, Li Q W, Chen J X and Jing F Q 2005 *Chin. Phys. Lett.* **22** 747
[9] Ma X J, Liu F S, Sun Y Y, Zhang M J, Peng X J and Li Y H 2011 *Chin. Phys. Lett.* **28** 044704
[10] Li Y L, Liu F S, Ma X J, Li Y L, Yu M, Zhang J C and Jing F Q 2009 *Rev. Sci. Instrum.* **80** 139
[11] Ma X J, Liu F S, Zhang M J and Sun Y Y 2011 *Chin. Phys. B* **20** 068301
[12] Li Y L, Liu F S, Zhang M J, Ma X J, Li Y L and Zhang J C 2009 *Chin Phys. Lett.* **26** 038301
[13] Ma X J, Liu F S and Jing F Q 2010 *Sci. China Ser. G* **53** 802
[14] Jing F Q 1999 *Experiment Equation of State*, 2nd edn. (Beijing: Science Press) p. 239, pp. 204–209 (in Chinese)
[15] Marsh S P 1980 *LASL Shock Hugoniot Data* (Berkley: University of California Press) p. 260
[16] Shi S C, Chen P S and Huang Y 1991 *J. High Press. Phys.* **3** 5