Viscosity of aluminum under shock-loading conditions*

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A reliable data treatment method is critical for viscosity measurements using the disturbance amplitude damping method of shock waves. In this paper the finite difference method is used to obtain the numerical solutions for the disturbance amplitude damping behaviour of the sinusoidal shock front in a flyer-impact experiment. The disturbance amplitude damping curves are used to depict the numerical solutions of viscous flow. By fitting the experimental data to the numerical solutions of different viscosities, we find that the effective shear viscosity coefficients of shocked aluminum at pressures of 42, 78 and 101 GPa are (1500±100) Pa·s, (2800±100) Pa·s and (3500±100) Pa·s respectively. It is clear that the shear viscosity of aluminum increases with an increase in shock pressure, so aluminum does not melt below a shock pressure of 101 GPa. This conclusion is consistent with the sound velocity measurement.

Keywords: shear viscosity, aluminum, shock-load

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1. Introduction

Generally, observing the propagation of seismic waves generated by earthquakes and explosions can be used to understand mantle convection and the outer-core of Earth.[1−5] Predicting the evolution of waves inside Earth requires material parameters to describe its dispersive and dissipative properties. Viscosity, which is described by shear and bulk coefficients according to Newtonian viscous fluid theory[1] at high pressures and high temperatures, is necessary because it is one of the important factors governing the flow behaviours of viscous fluids for relevant substances. However, data of these quantities for metals are very lacking because direct measurements become very difficult at high pressures of Mbar and high temperatures of several thousand Kelvin.

The oscillatory damping method, which is based on the time evolution of small harmonic perturbations in front of a shock wave propagating in the investigated substance, is considered to be an effective way to directly investigate the shear viscosity of material under shock compression.[6] However, how to generate a harmonic disturbed shock wave in experiment and how to analyse the effect of viscosity in data treatment have been open questions for several decades.[7] The flyer-impact technique was first developed by one of the present authors to measure the disturbance amplitude of the shock front in aluminum in a shock pressure range of 42 GPa–101 GPa.[8−10] The present paper aims to give the numerical solution of the sinusoidal disturbance amplitude oscillatory damping behaviour of a shock front in a flyer-impact experiment, which is first obtained by solving the two-dimensional difference Navier–Stokes equation. The effective shear viscosity coefficients (not considering the elastic–plastic property) of aluminum in a shock pressure range of 42 GPa–101 GPa can then be analysed.

2. Outline of the flyer-impact experiment

The flyer-impact experiment technique[8−10] for producing a small-disturbed sinusoidal shock wave in a metal sample is schematically shown in Fig. 1. The shock wave is generated by letting a high-speed planar flyer of the same material from a two-stage light-gas gun impact a metal sample. The disturbance on the shock front is introduced by making use of a wedged sample with some sinusoidal grooves on its impact surface.

The arrival times of the shock wave at the back surface of the wedged sample are detected, separately, by five pin groups of electric pins without an insulation layer on their heads, which are located at positions corresponding to the crests and troughs of corrugated

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shock in order to determine the amplitude of perturbation. The alignment of a typical group of electric pins and its electrical circuit are also shown in Fig. 1. In this way, the times when the shock wave arrives in turn at each pin of the group can be recorded by a single channel of an oscilloscope. By the flyer-impact experiment, we obtain the oscillatory damping process of the disturbance amplitude at shock pressures of 42, 78 and 101 GPa.

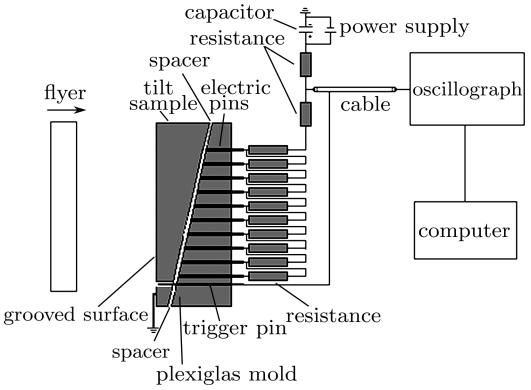


Fig. 1. Systematic diagram of the flyer-impact method.

3. Numerical method

The two-dimensional Eulerian form of hydrodynamic equations[1] (including the mass, momentum and energy equations) can be expressed as

$$\frac{\partial \rho}{\partial t} + u_x \frac{\partial \rho}{\partial x} + u_z \frac{\partial \rho}{\partial z} = -\rho \left(\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z} \right), \quad (1)$$

$$\rho \left(\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_z \frac{\partial u_x}{\partial z} \right) = \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xz}}{\partial z},$$

$$\rho \left(\frac{\partial u_z}{\partial t} + u_x \frac{\partial u_z}{\partial x} + u_z \frac{\partial u_z}{\partial z} \right) = \frac{\partial \tau_{zz}}{\partial z} + \frac{\partial \tau_{xz}}{\partial x}, \quad (2)$$

$$\rho \left(\frac{\partial E}{\partial t} + u_z \frac{\partial E}{\partial x} + u_z \frac{\partial E}{\partial z} \right) = \tau_{xx} \frac{\partial u_x}{\partial x} + \tau_{zz} \frac{\partial u_z}{\partial z} + \tau_{xz} \left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x} \right), \quad (3)$$

where ρ and E are the density and energy of the shocked material respectively; u_x and u_z are the particle velocities in the x direction and the z direction, respectively; the stress tensor in the (x, z) coordinate frame is given by the components

$$\tau_{xx} = -P + q + \frac{2}{3}\eta \left(2\frac{\partial u_x}{\partial x} - \frac{\partial u_z}{\partial z} \right) + \kappa \left(\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z} \right),$$

$$\tau_{xz} = \tau_{zx} = \eta \left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z} \right),$$

$$\tau_{zz} = -P + q + \frac{2}{3}\eta \left(2\frac{\partial u_z}{\partial z} - \frac{\partial u_x}{\partial x} \right) + \kappa \left(\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z} \right), \quad (4)$$

with P being the pressure, η the shear viscosity, κ the bulk viscosity, and q is expressed as[11]

$$q = \alpha \rho \frac{\partial u_x}{\partial x} \quad \text{or} \quad q = \alpha \rho \frac{\partial u_z}{\partial z}. \quad (5)$$

Here, α is the artificial viscosity coefficient used to suppress the numerical noise and meet the requirement for flow continuity at the shock front.[12]

The reference frame and the gridding scheme are shown in Fig. 2, the cell number in the x and z directions are 6000 and 2000, of which the simulation lengths are 18 mm and 6 mm, respectively. The time step is 1 ps. The planer flyer is assumed to move along the x axis. The sinusoidal geometrical disturbance with wavelength λ and initial amplitude h is added to the impact surface of the wedged sample.

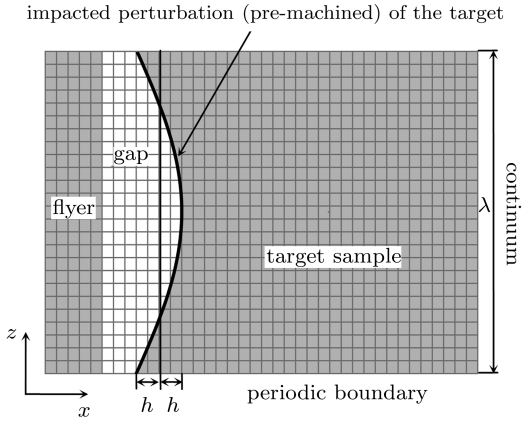


Fig. 2. Gridding scheme and boundary condition.

The simulation begins with the movement of the planer flyer, figure 2 depicts the initial state of the simulation flow. In the areas of the flyer, gap and sample, the initial mass velocity, pressure, density and internal energy, which satisfy the Rankine–Hugoniot relation, are shown in Table 1.

Table 1. Initial condition of simulated flow field.

Area	u_x/km·s^{-1}	u_z/km·s^{-1}	P/GPa	ρ	E/J
Flyer	3.857 (42 GPa) 6.055 (78 GPa) 7.023 (101 GPa)	0	0	ρ_0	0
Gap	0	0	0	$10^{-6}\rho_0$	0
Sample	0	0	0	ρ_0	0

The continuum boundary is applied to the left and right sides, and the periodic condition is assumed for up and down boundaries to assure the periodicity of disturbance, i.e. the simulation length in the z direction is the right wavelength λ of the disturbance.

When the initial condition is determined, the formation of the shock wave and its shape evolution of the shock front are governed by hydrodynamic equations and substance properties. The capturing scheme of the maximum pressure gradient and the model for considering viscosity behind the shock front[13] are used in this paper. The initially disturbed shock wave is completely formed when the gap is just closed. Then, the oscillatory damping of its disturbance amplitude starts and the relative amplitude ($= a/a_0$, the ratio of the disturbed amplitude a to the initial amplitude a_0) and the relative distance ($= x/\lambda$, the ratio of the propagation distance x of the shock front to the wavelength λ of the sinusoidal disturbance) can be figured out. So the evolution of the shock wave can be described by the oscillatory damping curve of the disturbance amplitude determined by the above two factors.

4. Results

According to the setup of flyer-impact experiment, both the flyer and the sample are aluminum. The equation of state (EOS) of aluminum is given by its Hugoniot EOS and Gruneisen EOS. Initial density ρ_0 and Hugoniot parameters c_0 and s are 2.73 g/cm^3, 5.4 km/s, and 1.337, respectively.[8] Gruneisen parameter γ_0 at the initial state is 2.16, and $\rho\gamma = \rho_0\gamma_0$ is supposed. The disturbed wavelength λ of the impact surface of the wedged sample is 6 mm, which is assumed to remain unchanged in the whole shock course, and the initial amplitude h is determined by relative (on wavelength) initial amplitude $h/\lambda(= 0.05)$.

It is found that the oscillatory damping curve is independent of the artificial viscosity and insensitive to the bulk viscosity coefficient κ, so the shear viscosity coefficient η is assumed to be equivalent to the bulk viscosity coefficient κ. The viscosity effects in the flyer-impact experiment at shock pressures of 42, 78, and 101 GPa are studied. Figure 3 is a typical figure showing the oscillatory damping numerical solutions of viscous flow at a pressure of 101 GPa. It is clear that the disturbance amplitude quickly decreases in the early period and the viscosity effects are not apparent. With the propagation of the sinusoidally disturbed shock wave, the damping rate of amplitude is slowed down by viscosity effects in the later period. It is clear that both the phase of the zero-amplitude point (the value of the relative distance at the first position where the relative amplitude is zero) and the maximum amplitude of reverse-phase oscillation are sensitive to the real viscosity. When the viscosity coefficients rise, the zero-amplitude point is delayed; instead, the maximum amplitude of reverse-phase oscillation is reduced.

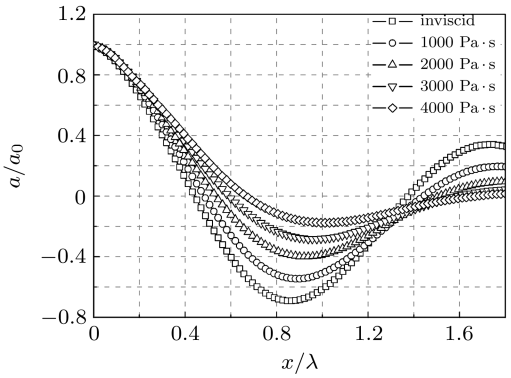


Fig. 3. Disturbance amplitude damping curves of the shock front in viscous flow at a pressure of 101 GPa.

By fitting the experimental data to numerical solutions of different viscosities, we find that the effective shear viscosity coefficients of shocked aluminum at pressures of 42, 78, and 101 GPa are (1500±100) Pa·s, (2800±100) Pa·s, and (3500±100) Pa·s respectively. The experimental data and relevant numerical solution under the condition of 101 GPa is shown in Fig. 4. Good agreement is reached between them. The other two experiments are the same as the above one. It is demonstrated that the present numerical method gives the right solutions for the development of shock wave with sinusoidal shock in a flyer-impact experiment. The errors are determined by the experiment and the numerical simulation.

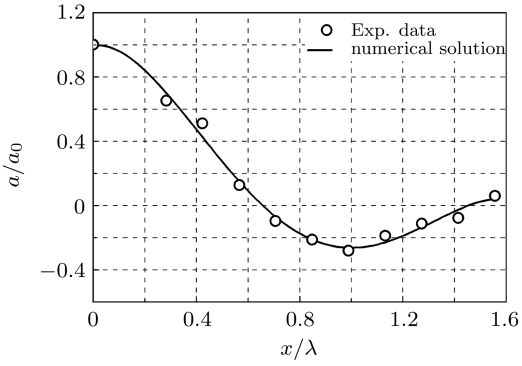


Fig. 4. Disturbance amplitude damping data of the shock front in a flyer-impact experiment and the numerical solution in viscous flow with $\eta = \kappa = 3500$ Pa·s at a pressure of 101 GPa.

It is clear that the effective shear viscosity of aluminum increases with the shock pressure increasing, which is shown in Fig. 5, so aluminum does not melt below a shock pressure of 101 GPa. This conclusion is consistent with the result of sound velocity measurement.[14]

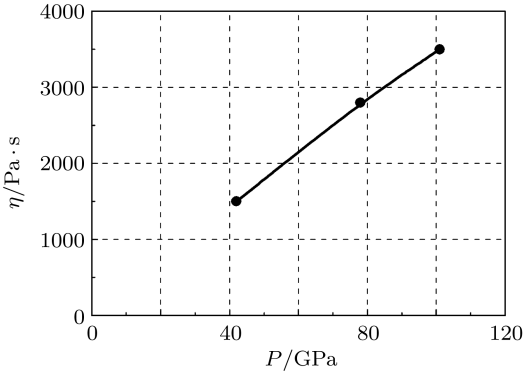


Fig. 5. Variation of the shear viscosity coefficient of aluminum with shock pressure.

5. Conclusions and discussion

The finite difference method is used to obtain the numerical solution for the amplitude damping curve of geometrical disturbance on a shock front by solving two-dimensional hydrodynamic equations in Eulerian form for viscous flow in a flyer-impact experiment. Fitting the experimental data to relevant numerical solutions of different viscosities, the effective shear viscosity coefficients of aluminum are confirmed to be (1500±100) Pa·s, (2800±100) Pa·s, and (3500±100) Pa·s at shock pressures of 42, 78, and 101 GPa, respectively. These results are higher than those obtained through analysis using Miller and Ahrens' analytic solutions, which is attributed to the drawbacks of the analytic solution by Miller and Ahrens. We believe that the above results are more reasonable because they are obtained from a comprehensive simulation for the full-shocked perturbation evolving process under the condition of the flyer-impact experiment.

The effective viscosity coefficient is measured by the flyer-impact method to be about 10^3 Pa·s, which is greatly different from that measured by the static high pressure method. In dynamic high pressure experiments, the shear viscosity is related to dislocation motion in solid material, while in static high pressure experiments it is related to the diffusion motion of atoms or molecules in liquid material. Therefore, there are different physical meanings of shear viscosity in dynamic and static high pressure experiments, and there is no comparability between these results.

From the flyer-impact experiment results, the effective shear viscosity of aluminum increases with the shock pressure increasing and it is clear that the metal aluminum does not melt below a shock pressure of 101 GPa, which is consistent with the result of sound velocity measurement.

References

[1] Miller G H and Ahrens T J 1991 *Rev. Mod. Phys.* **63** 919
[2] Buffett B A 1997 *Nature* **388** 571
[3] Secco R A 1995 *Viscosity of the Outer Core* (New York: American Geophysical Union) p. 159
[4] Mineev V N and Funtikov A I 2004 *Phys. Usp.* **47** 671
[5] Xi F and Cai L C 2009 *Chin. Phys.* B **18** 2898
[6] Sakharov A D, Zaidel R M and Mineev V N 1965 *Sov. Phys. Doklady.* **9** 191
[7] Ma X J, Liu F S Li Y L, Zhang M J, Li Y H, Sun Y Y, Peng X J and Jing F Q 2010 *Acta Phys. Sin.* **59** 4761 (in Chinese)
[8] Liu F S, Yang M X, Li Q W, Chen J X and Jing F Q 2005 *Chin. Phys. Lett.* **22** 747
[9] 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
[10] 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
[11] Mader C L 1998 *Explosives and Propellants* 2nd edn. (San Francisco: CRC Press) p. 327
[12] Vonneumann J and Richtmyer R D 1950 *J. Appl. Phys.* **21** 232
[13] Ma X J, Liu F S and Jing F Q 2010 *Sci. Chin.* Ser. G **53** 802
[14] Furnish M B, Chhabildas L C and Reinhart W D 1999 *Int. J. Imp. Eng.* **23** 261