Shear viscosity of aluminum studied by shock compression considering elasto-plastic effects*

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The strength always exists before the material melts. In this paper, the viscoelastic-plastic model is applied to improve the finite difference method, and the numerical solutions for the disturbance amplitude damping behavior of the sinusoidal shock front in a flyer-impact experiment are obtained. When the aluminum is shocked to 101 GPa, the effect of elasto-plasticity on the zero-amplitude point of the oscillatory damping curve is the same as that of viscosity when $\eta = 700$ Pa·s, and the real shear viscosity coefficient of the shocked aluminum is determined to be about 2800±100 Pa·s. Comparing the experiment data with the numerical results of the viscoelastic-plastic model, we find that the aluminum is close to melting at 101 GPa.

Keywords: shock, shear viscosity, elastoplasticity

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1. Introduction

The viscosity of a substance at high pressure of megabars and high temperature of several thousand Kelvin is one of the important parameters for predicting the evolution of seismic waves that are generated by earthquakes and understanding the mantle convection in the earth.[1–5] Some experimental methods have been employed to determine the viscosity of materials under high pressure. The indirect indicators include the fluorescence lifetime in glycerin[6] and the electrical conductivity measurement of weak electrolyte solutions.[7] The direct measurements include the viscous drag on an embedded cylinder[8] and the oscillatory damping of a sinusoidal shock front.[9] The latest measurement applied by Sakharov *et al.* relies on the correlation between the viscosity of a shock compressed material and the amplitude oscillation of an initial sinusoidal disturbance on the shock front in the concerned substance. However, Sakharov only gave one experimental result until now even though they have investigated several metals, and some problems should been validated.[10] To simplify the measurement of Sakharov *et al.*, the authors[11–15] put forward a flyer-impact technique and determined the effective shear viscosity coefficients of aluminum and iron at the high pressure of a megabar using the finite difference method.[16]

The fluid approximation was used in the finite difference method. The shear modulus of a material is a physical parameter denoting the ability of resisting to a shearing force. However, it cannot always be assumed to be negligible in shocked materials before melting.[17,18] Thus in this paper, we improve the numerical method by considering the effect of the strength on the disturbance amplitude damping behavior of a sinusoidal shock front in the sample. Consequently, the real viscosity coefficient of a metal at high pressure and high temperature can be constrained.

2. Brief of experiment

The flyer-impact technique[11,12] mainly consists of two steps. One is to generate a small-perturbed sinusoidal shock wave. The other is to measure the evolution of the disturbed shock front. A small-disturbed sinusoidal shock wave in the metal sample can be produced by the impact of a planar flyer on the sinusoidally grooved surface of a wedge shape. The planar flyer is accelerated by a two-stage light-gas gun. Five groups of electric pins are pinned to the points where the crest and trough of the shock front will arrive for measuring the evolution of the disturbed shock front. These pins are inserted into an ingenious circuit, so the arrival time of the shock front at the back surface of the wedged sample can be detected and recorded by an oscilloscope. The shape of the perturbed shock front and its development with the propagation distance can be approximately mapped out by simply connecting the time points of the same thickness with sinusoidal trend curves, as shown in Fig. 1 for the shot at 101 GPa. It is obvious that the behaviors of damping and oscillation of the perturbation amplitude can be figured out clearly.

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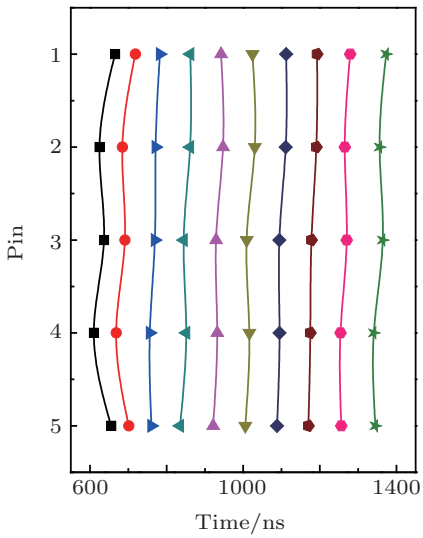


Fig. 1. (color online) Perturbation development with propagation time of sample Al at 101 GPa.

3. Numerical simulations

Compared with the setup of the flyer-impact experiment, the reference frame and the gridding scheme are designed as shown in Fig. 2. The sinusoidal geometrical disturbance with initial amplitude h (0.3 mm) and wavelength λ (6 mm) is added to the impact surface of the wedged sample. The disturbed wavelength is supposed to be unchanged during the whole shock course.

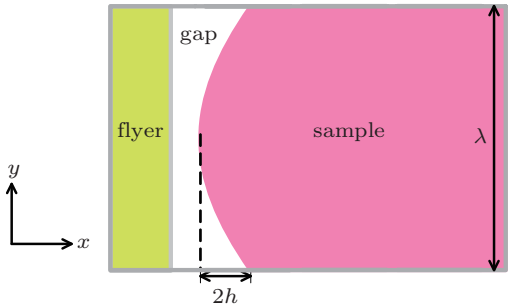


Fig. 2. (color online) Reference frame and gridding scheme.

The planer flyer is assumed to go along the x axis. Only in this area the initial mass velocity along x is not zero and determined by the flyer velocity in the experiment. The density of the flyer and the sample is ρ_0, and the density of the gap is assumed to be $10^{-6}\rho_0$ for satisfying the continuous medium hypothesis. The pressure, the internal energy, and the initial mass velocity along y in all areas are zero. The above physics quantities meet the relationship of Rankine–Hugoniot between the shock and the particle velocity ($D = C_0 + sU$), and the relation $\rho\gamma = \rho_0\gamma_0$ about the Gruneisen parameter is assumed. The continuum boundary condition is applied to the left and the right sides, and the periodic boundary condition is assumed for the up and the down boundaries to assure the periodicity of the perturbation.

The whole viscoelastic-plastic flow is continuous, the shear modulus function is implanted into a two-dimensional Eulerian code,[19] in which the deviatoric stress S during loading is calculated through

$$\begin{cases} \dot{S} = 2G\dot{e}, & S \leq \dfrac{2}{3}Y, \\ S = \frac{2}{3}Y, & S > \dfrac{2}{3}Y, \end{cases} \tag{1}$$

where e is the deviatoric strain, and the dot over the variable means a time derivative. Here G and Y are the elastic shear modulus and the yield strength, respectively, which are modeled at pressure P and temperature T as[20]

$$G = G_0\left[1 + \left(\frac{G'_P}{G_0}\right)\frac{P}{\eta^{1/3}} + \left(\frac{G'_T}{G_0}\right)(T - 300)\right], \tag{2}$$

$$Y = Y_0[1 + \beta(\varepsilon + \varepsilon_{\rm i})]^n \times \left[1 + \left(\frac{Y'_P}{Y_0}\right)\frac{P}{\eta^{1/3}} + \left(\frac{G'_T}{G_0}\right)(T - 300)\right], \tag{3}$$

where $\eta = V_0/V$ is the compression defined as the initial specific volume V_0 divided by the one under the Hugoniot stress, β and n are work-hardening parameters, and $\varepsilon_{\rm i}$ is the initial equivalent plastic strain, which normally equals to zero. The subscript 0 refers to the reference state ($T = 300$ K, $P = 0$, $\varepsilon = 0$). The primed parameters with subscripts P and T imply the derivatives of the parameters with respect to the pressure and the temperature at the reference state, respectively. The hydrodynamic equations of state (EOSs) used in the numerical simulations are the Mie–Gruneisen EOS. The relevant parameters for aluminum in simulations are listed in Table 1.

Table 1. Parameters used in the constitutive equations and EOSs .

Material	G_0/GPa	Y_0/GPa	β	n	(G'_P/G_0)/TPa^{-1}	$(-G'_T/G_0)$/kK^{-1}	ρ_0/g·cm^{-3}	C_0/km·s^{-1}	s	γ_0
6061Al	27.6	0.29	125	0.1	65	0.62	2.704	5.35	1.34	1.97

The capturing scheme of the maximum pressure gradient and the model considering the viscosity behind the shock front[16] are used in this paper. The initially disturbed shock wave with an amplitude a_0 is completely formed when the gap is just closed. Then, the oscillatory damping of the perturbation amplitude starts, so the relative amplitude a/a_0 and the relative distance x/λ can be figured out, where a is the disturbed amplitude of the shock front at any time, and x is the

propagation distance from the initial disturbed shock front. Therefore, the evolution of the shock front can be described by the oscillatory damping curve of the perturbation amplitude defined by the relative distance and the relative amplitude.

4. Results and discussion

Aluminum shocked to pressure 101 GPa is chosen as an example. When only the elastoplastic effect is considered (the viscosity coefficient is zero), the oscillatory damping curve (Fig. 3) can be simulated. At the first stage, the perturbation amplitude experiences a decaying process until the zero-amplitude point at which the relative amplitude is firstly zero, then it rises to the maximum but in a reverse phase, and then decreases again. When $\eta = 700$ Pa·s, its characters are similar to those of a viscous fluid by comparing the position of the zero-amplitude point, which is extremely important for determining the physical characteristics of the continuous medium. Only at the late stage, the perturbation amplitude in the elastoplastic medium is smaller than that in the viscous fluid (Fig. 3). It is clear that when aluminum is shocked to 101 GPa, the influence of elastoplasticity to the perturbation amplitude of the shock front is equivalent to that of viscosity when $\eta = 700$ Pa·s by comparing the position of the zero-amplitude point.

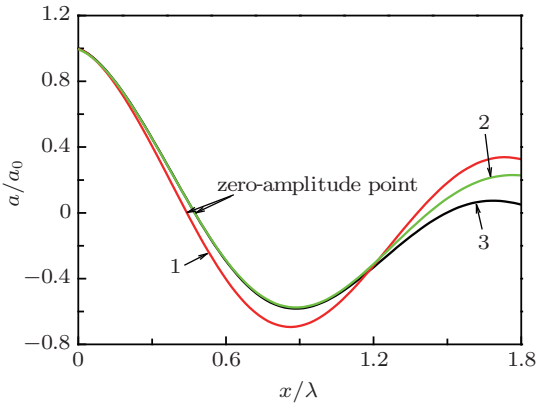


Fig. 3. (color online) Oscillatory damping curves of Al at 101 GPa (1 and 2 are respectively the ones at $\eta = 0$ Pa·s and $\eta = 700$ Pa·s, 3 is the only one considering elastoplasticity).

Based on the viscoelastic-plastic model, the oscillatory damping curves can be simulated when the viscosity coefficient is given. By using the least-square method to fit the disturbance amplitude damping data of the shock front in the flyer-impact experiment with the above numerical solutions, it is found that the real shear viscosity coefficient of the shocked aluminum at 101 GPa is about 2800±100 Pa·s (Fig. 4) based on the zero-amplitude point.

Using the fluid approximation, the authors[14] have simulated the oscillatory damping process of the perturbation amplitude of the shock wave propagating in the sample, and obtained the oscillatory damping curves. So the effective shear viscosity (ignoring the effect of the strength) of the aluminum shocked to 101 GPa is determined to be about 3500 Pa·s by comparing with the experimental data shown in Fig. 4.

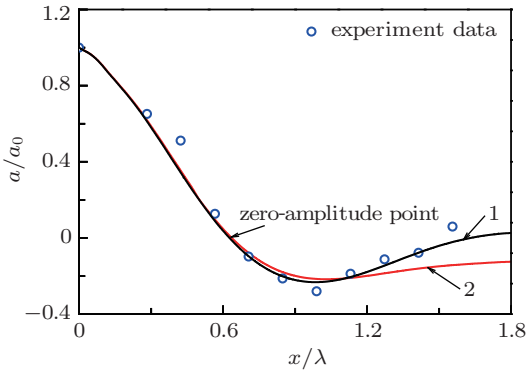


Fig. 4. (color online) Experiment data and numerical solutions when Al shocked to 101 GPa (1 is the result of the fluid model when $\eta = 3500$ Pa·s, 2 is the result of the viscoelastic-plastic model when $\eta = 2800$ Pa·s).

Comparing all the above results, we find that the experiment data for the late stage are in good agreement with the numerical solution of the fluid model. That is to say, the aluminum shocked to 101 GPa is nearly melted when the shock wave attenuates to the late stage.

5. Conclusion

Based on the conservation equations (including mass, momentum, and energy equations), EOSs, and constitutive equations, numerical solutions are obtained, in which the viscosity and the elastoplasticity are both considered. The solutions can reflect the evolution of the disturbed shock wave in the experimental sample. The aluminum shocked to pressure 101 GPa is chosen as an example. With the results of the viscoelastic-plastic model, we find by comparing the position of the zero-amplitude point on the oscillatory damping curves that when $\eta = 700$ Pa·s, the elastoplasticity and the viscosity have the same effect on the development of the perturbation amplitude of the shock front. The real shear viscosity coefficient of the shocked aluminum at pressure 101 GPa is about 2800±100 Pa·s, which is found by analyzing the experiment data using the numerical solutions of the viscoelastic-plastic model. The aluminum is close to melting when the shock pressure is 101 GPa.

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