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Effective Shear Viscosity of Iron under Shock-Loading Condition *

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We combine the flyer-impact experiment and improve the finite difference method to solve whether the shear viscosity coefficient of shock iron is more reliable. We find that the numerical simulated profile agrees well with the measured one, from which the determined effective shear viscosity coefficients of shocked iron are 3000 ± 100 *Pa·s and* 4000 ± 100 *Pa·s, respectively, at 103 GPa and 159 GPa. These values are more than* 2000 ± 300 *Pa·s of Li Y L et al.[Chin. Phys. Lett. 26 (2009) 038301] Our values are more reasonable because they are obtained from a comprehensive simulation for the full-shocked perturbation evolving process.*

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Iron accounts for 90% of the Earth's core and the inner core consists nearly of pure iron,[1] which is observed by the propagation of seismic waves that are generated by earthquakes and explosions.[2−5] Prediction of the evolution of waves inside the earth requires the materials' parameters describing their dispersive and dissipative properties. Viscosity, which is described by shear and bulk coefficients according to Newtonian viscous fluid theory,[5] is necessary because it is one of the important factors for governing the flow behavior of viscous fluids for related substances at high pressures and high temperatures. Recently, many publications have been devoted to measurements of the shear viscosity and diffusivity of liquid iron at pressures up to 20 GPa.[6,7] However, the pressures are 133 GPa and 330 GPa at the outer core bounders and 360 GPa at the Earth's center.[1] Thus the viscosity coefficient of iron at high pressures of Mbar and at high temperatures of several thousands of Kelvin is expected. However, data of these parameters are very lacking for metals because direct measurements become very difficult under those extreme conditions.

The oscillatory damping method, which is based on the time evolution of small harmonic perturbations on the front of a shock wave propagating in the investigated substance, is considered as an effective way to directly investigate the shear viscosity of material under shock compression.[8] However, how to generate harmonic disturbed shock wave in experiment and how to analyze the effect of viscosity in data treatment are still open questions for several decades.[9] The flyer-impact technique was first developed by one of the present authors to measure the disturbance amplitude of shock front in the sample of aluminum and iron at shock pressure 42–159 GPa,[10−12] and the corresponding effective shear viscosity coefficient is deduced from Miller and Ahrens' formula. However, we find that Miller and Ahrens' formula can not be used to treat the experimental data of Sakharov and flyer impact for their harsh requirements.[13] Ma *et al.*[9] obtained the numerical solutions for disturbance amplitude damping behavior of sinusoidal shock front in a viscous flow by solving the hydrodynamic Eulerian differenced equations of a two-dimensional flow. The reliability of the above solutions is proved by good agreement between the numerical solution and the analytic one for an inviscid and lower viscous fluid about a continuous flow. According to the setup of flyer-impact experiments,[10−12] the initial flow which can not be expressed by some confirmable formulas will be singularly complex because of existence of gaps between the flyer and sample. Miller and Ahrens[5] found that the analytic solution is sensitive to the initial condition. Thus, the original finite difference method[9] can not be used directly to analyze the experimental data. That is to say, we must improve the numerical method for the flyer-impact experiment.

In this Letter, we give the flyer-impact experimental result of shocked iron sample at 159 GPa and analyze it using the numerical solutions of the sinusoidal disturbance amplitude oscillatory damping behavior of shock front by an improved finite difference method.

The flyer-impact experiment technique, by which a small-disturbed sinusoidal shock wave in the metal sample can be produced, is introduced by Liu *et al.*[10] The shock wave is generated by letting a high-speed planar flyer of the same material from two-stage light-gas gun impact a metal sample. The disturbance on the shock front is introduced by use of a wedged sample with some sinusoidal grooves on its impact surface. The schematic experimental design is shown in Fig. 1, which is the same as the setup in Refs. [10–12]. The arrival times of shock wave at the back surface of the

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wedged sample are detected by five electric pin groups in electrical circuits, which are located at the positions corresponding to the crests and troughs of corrugated shock in order to determine the amplitude of perturbation. In this way, the times when shock wave arrives in turn at each pin of the group can be recorded by a single channel of an oscilloscope.

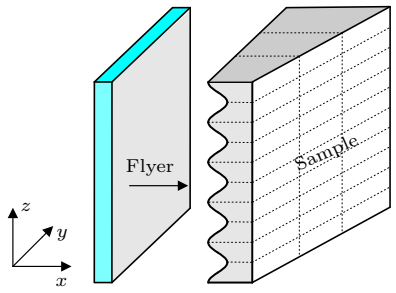


Fig. 1. Schematic design of the flyer-impact experiment setup, as the same as Refs. [10–12].

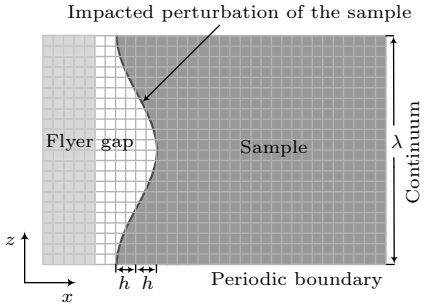


Fig. 2. The gridding scheme and boundary condition.

On the basis of the flyer-impact experiment design, Li *et al.*[12] obtained the oscillatory damping curve of the disturbance amplitude of shocked iron at 103 GPa. For finding the effective shear viscosity coefficients of iron at higher pressure, we measure the oscillatory damping process of the disturbance amplitude of shocked iron at 159 GPa when the speed of iron flyer is 5.095 km/s.

Based on the finite difference method, the movement of flow field is governed by two-dimensional hydrodynamic equations.[9] The equation of state (EOS) of iron is given by its Hugoniot EOS and Gruneisen EOS. Its initial density ρ_0, Hugoniot parameters c_0 and s, are 7.85 g/cm^3, 3.935 km/s and 1.578, respectively.[14] Its Gruneisen parameter γ_0 at the initial state is 1.78,[14] and $\rho\gamma = \rho_0\gamma_0$ is supposed.

Compared with the flyer-impact experiment setup[10–12] shown in Fig. 1, the reference frame and the gridding scheme are designed as Fig. 2. The cell numbers 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 be along the x-axis. The disturbed wavelength λ of the impact surface of the wedged sample is 6 mm, which is supposed to keep unchanged in the whole shock course and the initial amplitude h is determined by relative (on wavelength) initial amplitude $h/\lambda(= 0.05)$.

Table 1. The initial condition in simulated flow field.

Area	u_x(km/s)	u_z(km/s)	P(GPa)	ρ	E(J)
Flyer	5.095	0	0	ρ_0	0
Gap	0	0	0	$10^{-6}\rho_0$	0
Sample	0	0	0	ρ_0	0

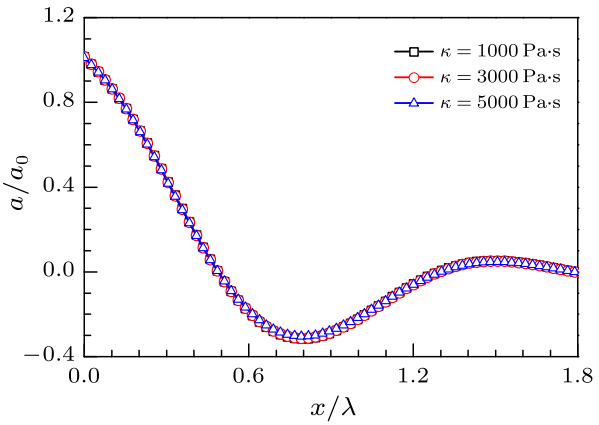


Fig. 3. Disturbance amplitude damping curves with different bulk viscosity coefficients when shear viscosity is 2000 Pa·s at pressure of 159 GPa.

The simulation begins from the movement of planer flyer. Figure 2 depicts the initial state of 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 listed in Table 1. Especially, we point out that the density of gaps is supposed to be $10^{-6}\rho_0$ for satisfying the continuous medium hypothesis.

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

When the initial condition is defined, the formation of shock wave and the 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 of considering viscosity behind of shock front[9] are used in this study. The initially disturbed shock wave is completely formed when the gap just is closed. Then, the oscillatory damping of its disturbance amplitude starts and the relative amplitude a/a_0, i.e., the ratio of the disturbed amplitude a to the initial amplitude a_0 and the relative distance x/λ, i.e. the ratio of the propagation distance x of the shock front to the wavelength λ of the sinusoidal disturbance, can be figured out. Thus the evolution of the shock wave can be described by the oscillatory damping curve of the dis-

turbance amplitude defined by the above two factors.

It is found that the oscillatory damping curve is independent of the artificial viscosity and insensitive to the bulk viscosity coefficient κ, as shown in Fig. 3, so the shear viscosity coefficient η is supposed to be equivalent to the bulk viscosity coefficient κ.

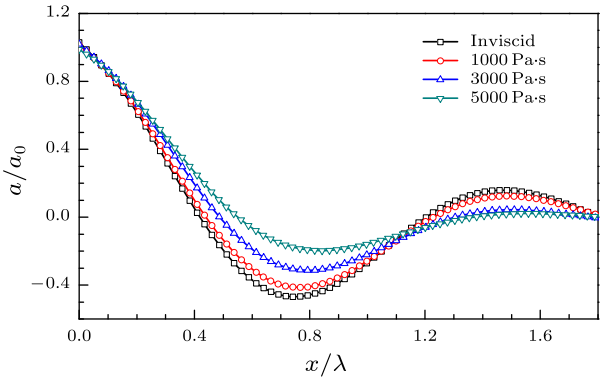


Fig. 4. Disturbance amplitude damping curves of shock front in viscous flow at pressure of 159 GPa.

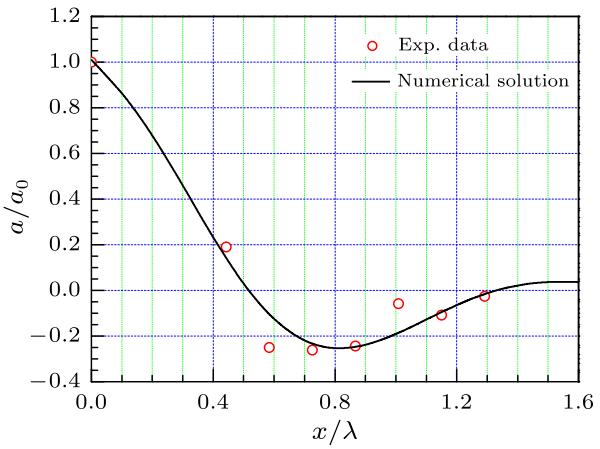


Fig. 5. The disturbance amplitude damping data of shock front in the flyer-impact experiment and the numerical solution in viscous flow with $\eta = \kappa = 4000$ Pa·s at pressure 159 GPa.

The viscosity effect in the flyer-impact experiment at shock pressure 159 GPa is studied. Figure 4 depicts the oscillatory damping numerical solutions of viscous flow. It is clear that the disturbance amplitude quickly decreases during the early period and the viscosity effects are unapparent. With the propagation of sinusoidally disturbed shock wave, the damping rate of amplitude slows down by viscosity effects in the later period. When the viscosity coefficients rise, the zero-amplitude point (the value of the relative distance at the first position where the relative amplitude is zero) is delayed. Instead, the maximum amplitude of reverse-phase oscillation is reduced.

By fitting the experimental data with the numerical solutions of different viscosities, we find that the effective shear viscosity coefficient of shocked iron at pressure 159 GPa is 4000 ± 100 Pa·s. The experimental data and the relevant numerical solution at 159 GPa is shown in Fig. 5, showing a good agreement. It demonstrates that the present numerical method gives the right solutions for development of shock wave with sinusoidal shock in the flyer-impact experiment.

Based on the above experimental analysis method, the effective shear viscosity coefficient of iron can be confirmed to be 3000 ± 100 Pa·s when the shock pressure is 103 GPa.[12]

Using the flyer-impact experimental design, the sinusoidal disturbance amplitude oscillatory damping behavior of shock front in the shocked iron sample at 159 GPa is measured. For analyzing the experimental result, the numerical solution for the amplitude damping curve of geometrical disturbance on shock front by solving two-dimensional hydrodynamic equations of Eulerian form for a viscous flow in flyer-impact experiment is obtained by the improved finite difference method. Fitting the experimental data with relevant numerical solutions of different viscosities, the effective shear viscosity coefficients of iron are about 3000 ± 100 Pa·s and 4000 ± 100 Pa·s respectively at shock pressure 103 GPa and 159 GPa. It is clear that the effective shear viscosity of iron increases with the shock pressure within 103 GPa to 159 GPa. The above results are higher than that analyzed by using Miller and Ahrens' analytic solutions. It is attributed to the drawbacks of the analytic solution by Miller and Ahrens. We believe that the present result is more reasonable because it is obtained from a comprehensive simulation for the full-shocked perturbation evolving process under the condition of flyer-impact experiment. In a future time, we would obtain more viscosity coefficients by combining experiments and numerical methods and find their detailed variation with shock pressure. Consequently it will make for studying the movement of inner Earth and weapon physics.

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