Electrical conductivity of iron under shock compression up to 200 GPa

2002 J. Phys.: Condens. Matter 14 10849

(http://iopscience.iop.org/0953-8984/14/44/389)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **14** (2002) 10849–10854 PII: S0953-8984(02)39427-X

Electrical conductivity of iron under shock compression up to 200 GPa

Yan Bi, Hua Tan and Fuqian Jing

Laboratory for Shock Wave and Detonation Physics Research, Institute of Fluid Physics, China Academy of Engineering Physics, PO Box 919-111, Mianyang 621900, China

Received 1 June 2002
Published 25 October 2002
Online at stacks.iop.org/JPhysCM/14/10849

Abstract
The electrical conductivity of shock-compressed iron was measured up to 208 GPa by using an improved sample assembly in which the iron sample is encapsulated in a single-crystal sapphire cell. High-pressure shock compressions were generated by plate impact with a two-stage light-gas gun. The measured conductivity of iron varies from $1.45 \times 10^4\ \Omega^{-1}\ \mathrm{cm}^{-1}$ at 101 GPa and 2010 K, to $7.65 \times 10^3\ \Omega^{-1}\ \mathrm{cm}^{-1}$ at 208 GPa and 5220 K. After analysing these data together with those reported previously, we found that the Bloch–Grüneisen expression is valid for ε-iron in the pressure and temperature range up to 208 GPa and 5220 K.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The electrical conductivity (σ) of the earth's liquid outer core is a crucial parameter to investigate the geomagnetic field origination [1, 2]. If we assume the values of σ_{core} can be approximated by those of the major core constituent of Fe, the experimental results of σ for solid and, in particular, for liquid Fe at high pressures can be used as the basic input to construct the geomagnetic dynamo model. On the other hand, the high-pressure electrical conductivity of metals is also significant for shock temperature measurements. Theoretically, the high-pressure thermal conductivity K of metals is connected with the electrical conductivity σ via the Wiedemann–Franz formula. Due to the difficulty in measuring high-pressure electric conductivity for metals, experimental data have rarely been reported. Though the Bloch–Grüneisen expression was once used to estimate the electrical conductivity for metals under shock compression [3], the validity of it at megabar shock pressures is yet lacking in direct experimental verification.

The electrical conductivity of iron and its alloys has been measured previously, limited to a shock pressure below ~140 GPa [4–8], and all of the σ data fell inside the solid phase region. In those sample assemblies, epoxy resin is used to fill the gap around the sample between the alumina plates, used as insulators, to minimize the shunt effect. Because the shunting effect of

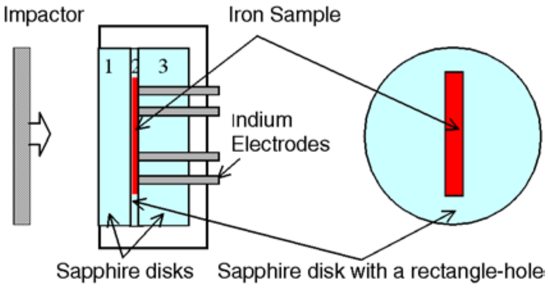

Figure 1. The assembly for measuring conductivity.

epoxy resin would emerge under high-pressure shock compression over ∼50 GPa, the σ_{Fe} thus obtained will be higher than the actual values under such pressure conditions. The purpose of this paper is to modify the sample assembly design, so as to measure σ_{Fe} reasonably at pressures above 50 GPa, and to test the validity of the Bloch–Grüneisen formula in a wider pressure region.

2. Experimental details

To avoiding the shunting effect, a thin sapphire disc with a rectangle hole is used to hold the sample in our experiments. Single-crystal sapphire has a high impedance and is a good insulator under shock compression up to 200 GPa [9]. The iron sample is manufactured to have the same geometry as that of the hole and is enclosed entirely in the sapphire cell, as shown in figure 1.

The rectangular iron sample used in the experiments has a high purity of 99.99%, is 0.5 mm thick, 32 mm long and 4 mm wide, and is embedded in sapphire disc 2. The iron sample and the sapphire discs are then sandwiched to form the sample assembly. For the thicker back sapphire disc, four small holes are drilled for holding electrodes. The two inner electrodes, separated 15 mm between their centres, are used for the output voltage measurement. The two outer ones, separated 27 mm between their centres, are used for constant current input. These electrodes are fabricated by casting molten indium into the drilled holes to make a better contact with the iron sample.

A two-stage light-gas gun is used to accelerate the flyer plate either made from tantalum or from copper to the desired velocity, which then impacts onto the sample assembly to produce a high-pressure shock wave in the sample. In the experiments, the flyer velocities are from 4.05 to 6.18 km s^{-1}. As the shock wave propagates from the front sapphire disc into the iron sample and then into the back sapphire disc, it should produce multiple reflections between the front sapphire/iron and the iron/back sapphire interfaces, and finally reach an equilibrium pressure in the iron sample equal to approximately the initial shock pressure in the sapphire discs. The pressure and particle velocity in the iron sample could be calculated using the standard impedance matching method [10]. The uncertainty in equilibrium pressure obtained using the above method is ∼1%. The Hugoniot parameters used for the impedance matching calculations are listed in table 1.

The four-electrode method [9] is used to measure the electrical conductivity. When the pulsed constant current flows through the shocked iron sample, the voltage difference between the two inner electrodes will be recorded. A typical experimental record at 101 GPa is shown in figure 2. The calculated pressure profiles at the front and back surface of the iron sample

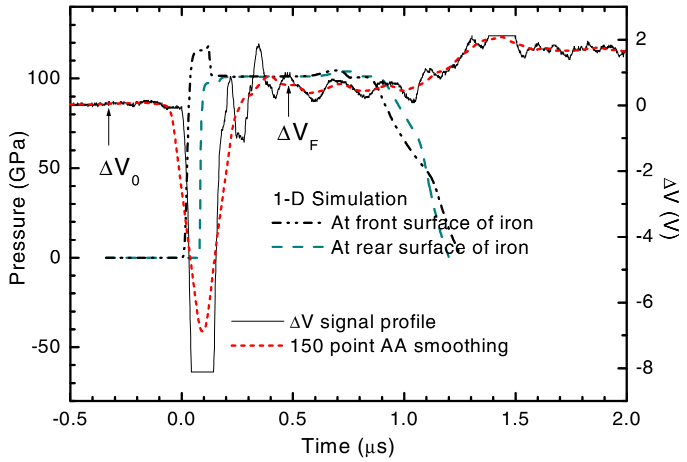

Figure 2. A typical record of ΔV for σ measurement of iron under shock compression. A calculated pressure history in iron is also illustrated as a reference for judging ΔV_F, at the equilibrium level.

Table 1. Hugoniot parameters used in calculations [11].

Material	Initial density (g cm^{-3})	C (km s^{-1})	S	γ_0
Fe	7.853	3.94	1.584	1.94 [12]
Al_2O_3	3.986	8.74	0.957	1.32 [13]
Ta	16.65	3.31	1.306	1.80 [10]
Cu	8.931	3.98	1.460	2.00 [10]

are also shown in figure 2, in which the time at which the first shock wave arrives at the front surface of the iron sample is chosen as the zero time point. The output voltage signal decreases rapidly at first due to shock-induced demagnetization of the iron sample resulting from the α–ε transition. The negative demagnetization pulse persists for about 0.2 μs; it then attenuates and gradually drops to a normal level. Since the electrical impedance is not perfectly matched in our recording system, the amplitude of the demagnetization signal vibrates around the normal level for about 0.8 μs.

Electrical conductivity σ is deduced from the experimental record according to Ohm's law. For the one-dimensional geometric configuration of our sample assembly and the one-dimensional shock compression process, we assume that the length and width of the sample is unchanged during the shock compression. The electrical conductivity of the final state σ_F can be calculated from

$$\sigma_F = \frac{L}{R_F X Z (v_F/v_0)} \tag{1}$$

where R_F is the electrical resistance at equilibrium state. L is the distance between the centres of the two inner electrodes from which the output voltage is recorded. X and Z are the width and thickness of the sample, respectively. v_F/v_0 is the ratio of the specific volumes of the equilibrium state to the initial zero-pressure state of the sample, which is calculated in a way similar to that of Matassov [8], details of which were described elsewhere [14]. For constant current condition, we have $R_F/R_0 = \Delta V_F/\Delta V_0$, where ΔV_F and ΔV_0 denote the voltage difference between the two inner electrodes at the equilibrium state and the initial state,

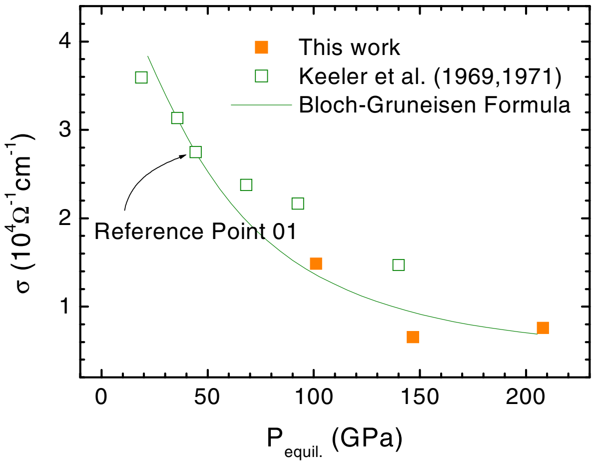

Figure 3. Electrical conductivity versus equilibrium pressure (P_{equil}) for iron.

Table 2. Electrical conductivity of shocked iron.

Flyer velocity (km s^{-1})	Initial pressure (GPa)	Equilibrium pressure (GPa)	v_F (cm^3 g^{-1})	Electrical conductivity (Ω^{-1} cm^{-1})
Cu/4.052	115.5	101.1	9.326×10^{-2}	1.45×10^4
Cu/5.389	173.4	146.7	8.842×10^{-2}	6.57×10^3
Ta/6.183	254.0	208.0	8.438×10^{-2}	7.65×10^3

respectively. Equation (1) then reduces to

$$\sigma_F = (\Delta V_0/\Delta V_F)(v_0/v_F)\sigma_0. \tag{2}$$

3. Results and discussion

The experimental results of the electrical conductivity of iron are listed in table 2 and plotted in figure 3. It shows that our σ data are much lower than those of Keeler and Royce's [7] above 100 GPa. This is consistent with the improvement of the modified sample assembly design due to the elimination of the shunting effect. At the highest pressure point, the initial shock pressure in iron reaches 254 GPa, and shock-induced melting occurs with a molten fraction χ of iron about 0.7 at the equilibrium state, which is calculated using a method similar to that of Tan and Ahrens [15] and Tan [16].

Although a dramatic decrease in σ would generally be expected when shock melting takes place, it does not happen in our experiment. The sole data point in the melting state is consistent with the general trend of the data in the solid phase region.

Generally, when $T > 0.5\Theta$, the electrical conductivity of the metal can be described by the Bloch–Grüneisen formula as [17]

$$\sigma = \frac{4A\Theta^2}{BT} \tag{3}$$

where T is the Kelvin temperature, Θ is the Debye temperature, A is the atomic weight and B is a material constant. Using the definition of the Grüneisen parameter

$$\gamma(v) = -\frac{\mathrm{d}\ln\Theta}{\mathrm{d}\ln v}. \tag{4}$$

Table 3. Parameters for the reference point 01 of iron.

P_{H01} (GPa)	P_{01} (GPa)	v_{01} (cm^3 g^{-1})	T_0 (K)	$\gamma_{01}{}^a$	σ_{01} (Ω^{-1} cm^{-1})
47.3	44.4	0.104	728	1.53	2.75×10^4

Electrical conductivity σ is connected with T and v by

$$\frac{\sigma}{\sigma_{01}} = \frac{T}{T_{01}} \exp\left[-2\int_{v_{01}}^{v} \frac{\gamma}{v}\,\mathrm{d}v\right] \tag{5}$$

where the subscript 01 denotes a reference point. In deducing equation (5) the phase transition is not considered. When using equation (5) to estimate the high-pressure electrical conductivity, the reference point 01 must be chosen in the same phase region.

The α–ε transition takes place at 13 GPa for iron and is complete at 40 GPa [19]. Above 40 GPa, iron remains in the ε phase until shock melting occurs at about 240 GPa. Between 13 and 40 GPa, iron is shocked into a mixed-phase region. Therefore, we chose Keeler's σ datum at 44.4 GPa as the reference point, which is just above the α–ε transition boundary. Also the epoxy resin is still a good insulator at pressures below 50 GPa, which is used as padding around the sample in Keeler's experiment. Parameters about the reference point of iron are listed in table 3.

For ε-iron $\gamma_\varepsilon = 1.7(\rho_0/\rho)^{0.7}$, where $\rho_0 = 8.28$ g cm^{-3} [19]. The temperature at the equilibrium state can be calculated from the initial shock temperature T_H along the isentropic path to the final pressure, and the T_H of iron is fitted from Anderson [19]. As illustrated in figure 3, the electrical conductivity for iron calculated from equation (5) is consistent with our experimental results, demonstrating that the Bloch–Grüneisen formula holds true for ε-iron at pressures and temperatures of 208 GPa and 5220 K.

4. Conclusion

It has been shown that the drilled sapphire disc configuration developed in this paper for electrical conductivity measurements of metals under strong shock compression can successfully eliminate the shunting effect caused by the previously used epoxy resin filler insulator, at least from ~50 to 200 GPa. The measured electrical conductivity data varies from 1.45×10^4 Ω^{-1} cm^{-1} at 101 GPa and 2010 K, to 7.65×10^3 Ω^{-1} cm^{-1} at 208 GPa and 5220 K. By examining our data and Keeler's data, we found that the Bloch–Grüneisen relation holds true for ε-iron at pressures and temperatures up to 208 GPa and 5220 K, which is very significant in studies of condensed matter physics and deep interior earth science. These results can be applied to estimate the conductivity within the earth's core, as iron is being proposed to be the major core constituent, especially for the solid inner core. Also it is of significance, in turn, to investigate the thermal and geomagnetic dynamo models of the earth's core.

Acknowledgments

The authors are grateful to Professor Min-guang Zhao for helpful discussions. Thanks are due to Dr Zongming Feng for his help in the design of the constant-current source. Thanks are also due to Mr Xiang Wang, Mr Yue Dong, Mr Lufeng Jia, Ms Wei Wang and Ms Qiuwei Fu for their help in the performance of the experiment. The National Natural Science Foundation of China under grant no 10032040 and the Science Foundation of China Academy of Engineering Physics, under contract no 970105, support this work.

References

[1] Glatzmaier G A and Roberts P H 1995 *Nature* **337** 203
[2] Braginsky S I and Roberts P H 1995 *Geophys. Astrophys. Fluid Dyn.* **77** 1
[3] Tang W, Zhang R, Jing F and Hu J 1998 *J. Appl. Phys.* **83** 2469
[4] Fuller P J A *et al* 1962 *Nature* **193** 262
[5] Wong J Y *et al* 1968 *Nature* **219** 714
[6] Keeler R N *et al* 1969 *Solid State Commun.* **7** 271
[7] Keeler R N *et al* 1971 *Physics of High Energy Density* (New York: Academic) p 106
[8] Matassov G 1977 *Report* UCRL-52322 Livermore, CA
[9] Weir S T *et al* 1996 *J. Appl. Phys.* **80** 1522
[10] Meyers M A 1994 *Dynamic Behaviour of Materials* (New York: Wiley) ch 5 p 124
Meyers M A 1994 *Dynamic Behaviour of Materials* (New York: Wiley) ch 7 p 179
[11] Ahrens T J and Johnson M L 1995 Mineral physics and crystallography *A Handbook of Physical Constants* ed T J Ahrens (Washington, DC: American Geophysical Union) p 143
[12] Li X, Zhou X, Wang F and Jing F 2001 *Chin. Phys. Lett.* **18** 85
[13] Anderson O L and Schreiber E 1968 *Rev. Geophys.* **6** 491
[14] Bi Y, Tan H and Jing F 2002 *Chin. J. High Pressure Res.* at press
[15] Tan H, Ahrens T J and Bass J D 1990 *High Pressure Res.* **2** 145
[16] Tan H 1996 *Chin. J. High Pressure Phys.* **10** 161
[17] Gerritsen A N 1956 Metallic conductivity *Handbuch der Physik* (Berlin: Springer)
[18] Andrews D J 1973 *J. Phys. Chem. Solids* **34** 825
[19] Anderson O L 1998 *Phys. Earth Planet. Inter.* **109** 179