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SHOCK TEMPERATURE MEASUREMENTS OF IRON TO 350 GPa

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Shock temperatures of iron have been measured to 350 GPa, using high quality well-characterized iron films deposited on diamond substrates. We have found an inflection in the (P,T)- iron Hugoniot between 250 GPa and 300 GPa, indicating iron melting at 6350 K and 6720 K, respectively. An extrapolation yields the iron melting temperature of 6870 (± 500) K at 330 GPa, the pressure of the Earth inner core-outer core boundary. In this paper, we will present this new iron melting data together with a brief description of the experimental method to measure the shock temperatures of iron.

INTRODUCTION

Determining the melting temperatures of iron near 330 GPa is probably one of the most important problem in geophysics. The iron melting temperature at 330 GPa provides an upper bound of the temperature at the Earth inner and outer core boundary (IOB), which would be a reference temperature for Earth core models. This temperature also determines the thermal gradient within the Earth and thereby, the dynamics of phase equilibria in the lower and upper mantle. For this reason the iron melting curve has been of considerable interest theoretically^{1,2} and experimentally.³⁻⁶

Recently, iron melting temperatures have been reported to 200 GPa in the diamond anvil cell laser heating experiments.³⁻⁵ Extrapolations of those results, however, not only give a large uncertainty in the IOB temperature ranging from 4000 K to 9000 K, but also yield phase diagrams that are qualitatively different from one another at the IOB conditions. An alternative, but more direct way of obtaining iron melting temperatures is by measuring shock temperatures. The method has previously been applied for iron by Ahrens and coworkers;³ however, the measured shock temperatures⁷ are greatly scattered and show no clear indication of melting.

The shock temperatures of metals are typically measured at the sample/window interface, which introduces several issues that must be addressed to obtain a reliable shock temperature. Those include characterization of the iron film

and iron film/window interface, optical property changes of window materials at high pressures and temperatures, and thermal conduction occurring across the interface.⁸ In this study we have developed the experimental techniques to address these issues and have measured the shock temperatures of iron to 350 GPa. In this paper we will summarize the experimental developments and present the shock temperature data showing a clear indication of melting.

EXPERIMENTS

Figure 1 shows the experimental setup to measure the shock temperatures of iron. High quality, well characterized iron films were prepared to about 2 μm in thickness by sputtering onto diamond substrates held at 300 $^{\circ}\text{C}$. The density of iron films differs from that of a bulk crystal by less than 1 %, smaller than the instrumental resolution. The iron film/diamond sample is sandwiched between a diamond-turned iron baseplate and a sapphire disk to minimize any thermal disturbance generated from a direct impact on an iron film. The shock wave is generated by impacting a Ta disk on the iron baseplate using a 2-stage gas gun.⁹ Shock pressures are determined using the impedance matching method and the equations of state for Ta¹⁰ and iron¹¹ that are accurately known.

Thermal emission from the iron/diamond interface is measured using a fast time-resolved emission system. A multi-channel optical fiber delivers the emission to two

detection systems: (1) a streak camera system records a quasi-continuous spectrum between 350 nm and 700 nm every 1.8 ns for a 100 ns time period, which is long enough to cover the shock events of interest, and (2) a photomultiplier tube system records time-resolved emission intensity at six discrete narrow wavelength bands. Because the optical fiber collects the emission from only a small central area of the sample (< 1 mm), the shock state of the sampling area is well defined in one-dimension and, thus, provides fast time resolution that primarily depends on the rise time of the recording electronics. Time and spectral resolution of the system are approximately 1 ns and 2 nm, respectively.

Figure 1. An experimental setup for the shock temperature measurements of iron.

RESULTS AND DISCUSSION

Typical time-resolved emission spectra of the shocked iron are shown in Fig 2. The intensity rise at 455 ns (a) is due to the shock-wave arrival at the iron/diamond interface. The broad nature of the spectra suggests that the emission is thermal. The emission intensity remains nearly constant during the shock wave transit through the diamond window, indicating that thermal equilibrium is achieved in the interface region and that the optical properties of the shocked diamond remain unchanged. This and other experiments reported here suggest that diamond is transparent in the entire pressure range to 300 GPa. The experiment is completed when the shock wave enters the sapphire disk at 483 ns (b), where the emission intensity rapidly decreases. This is likely due to partial opacity of the shocked sapphire.¹²

When the shock wave arrives at the interface, the pressure and temperature of iron are released to those of diamond. The temperature of the sample is determined by fitting the emission spectra to a gray-body radiation equation. However, due to thermal conduction occurring from shocked hot iron to shocked, but relatively cold, diamond, the interface temperature is substantially lower than that at the release shocked pressure.

A one-dimensional thermal conduction model¹³ is used to convert the interface temperature to the release temperature.

$$\frac{\delta}{\delta x} \left(\kappa \frac{\delta T}{\delta x} \right) = \frac{1}{\rho C} \frac{\delta T}{\delta t} \quad (1)$$

where κ , ρ and C , respectively, represent the thermal conductivity, density and heat capacity. Because of temperature dependence of the thermal conductivities of iron and diamond in particular, it is necessary to solve Eq (1) using temperature dependent thermal conductivity. It has been done numerically with microslabs of diamond and iron specimens in 1-ns time steps.

Figure 2. Time-resolved thermal emission spectra recorded by the streaking camera system (top) and PMT system (bottom).

The thermal conductivity of iron is approximated by the Wiedeman-Franz law using a linear scaling of the electrical conductivity measured along the Hugoniot.¹⁴ A phonon scattering model¹⁵ precisely describing the diamond thermal conductivity to 1200 K¹⁶ is modified to obtain the diamond thermal conductivity at high temperature and pressures. Here, the pressure-dependent Debye temperature and phonon frequency of diamond are obtained from Debye-Grüneisen approximation.¹⁷ The densities of iron and diamond are obtained from previously reported P-V Hugoniots.^{11,18} The heat capacity of iron is obtained by Dulong-Petit approximation 3R, and that of diamond is calculated by an Einstein model.¹⁹

The shock temperature T_h of iron on the principal Hugoniot is determined from the released shock temperature T_r by a Mie-Grüneisen thermal relation:¹⁹

$$T_h = T_r \exp \left(\int_{V_h}^{V_r} \frac{\gamma}{V} dV \right) \quad (2)$$

where the γ and V are the Grüneisen parameter and specific volume of iron, respectively. We approximate $\gamma/V = 16.6$.

Figure 3. Iron shock temperatures to 350 GPa, in comparison with the previous measurements (open circles and dash-dot lines) by Williams et. al. [3]. The open squares indicate the shock anomaly points [11].

Because of a good shock impedance match between diamond and iron at the pressure range of interest, this correction is typically less than 5 %.

Figure 3 presents the shock temperatures of iron between 150 GPa and 340 GPa, together with the previous measurements.³ The temperatures systematically increase with increasing pressure and clearly show an inflection at the pressure region between 235 GPa and 300 GPa, which we attribute to melting at 6350 K and 6720 K, respectively. It is also consistent with the shock anomaly pressure of 243 GPa previously observed in the sound velocity measurements and also interpreted as melting. The present measurements are in agreement with those reported previously below 250 GPa, but are substantially lower at higher pressures. The previous works also failed to observe any break in the Hugoniot temperature at melting.¹¹ Based on our measurements we estimate the melting temperature at the Earth IOB pressure 330 GPa to be 6830 K, lower than the previous estimate of 7600 K. On the other hand, the present melting data is still higher than the earlier estimates of Brown and McQueen's,¹¹ 5000-5700 K at 243 GPa and of 5800 K at 330 GPa.

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