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ELECTRICAL CONDUCTIVITY, DEMAGNETIZATION, AND THE HIGH-PRESSURE PHASE TRANSITION IN SHOCK-COMPRESSED IRON*

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The electrical conductivity and demagnetization of iron have been measured at pressures up to 370 kbar. The experimental results provide confirmation that the high-pressure ϵ-phase of iron is nonmagnetic, and indicate that the transition from α-phase to ϵ-phase may take place at pressures as low as 50 kbar.

THE EXISTENCE of a phase transition in iron in the vicinity of 130 kbar has been confirmed in both static and dynamic experiments.[1,2] It is now clear that this is not the well-known transition from body-centered cubic to face-centred cubic, but rather a transition to the hexagonal ϵ-phase.[3,4] Mössbauer experiments indicate that the ϵ-phase is nonferromagnetic.[5] In this note we present striking experimental confirmation of the nonmagnetic nature of this new phase. Our experiments also indicate that a partial transition to the ϵ-phase occurs in shocked iron far below 130 kbar.

The experimental configuration is shown in Fig. 1. The iron samples were thin foil strips, enclosed in an insulating sandwich of Wesgo 995 alumina ceramic. The leads were two cylindrical indium terminals attached to the ends of the iron strip. The whole assembly was mounted on an aluminum baseplate, resting on a pad of high explosive and a plane-wave lens with detonator attached.

When the detonator was fired, the explosive lens converted the point detonation into a plane wave which passed through the high-explosive pad into the baseplate and sample as a one-dimensional shock wave. The electronics were similar to those used by Fuller and Price[6] in previous shock-wave conductivity experiments, and consisted of a constant current source with a Tektronix 585 oscilloscope monitoring the voltage across the sample. The oscilloscope traces were triggered by a piezoelectric pin located at a level just below the sample. Alumina was chosen as the insulating material because of its close dynamic impedance match to iron and its high resistivity under shock pressures. Indium was chosen for the leads because of its close impedance match to alumina. This choice minimized possible shock-wave-induced shearing effects between the sample and the leads. The shock velocity was measured in the aluminum baseplate, and the conditions in the iron sample were calculated from the interface continuity conditions, using the Grüneisen equation of state for the shocked materials.

The experimental records are shown in Fig. 2. The first (Fig. 2a) is an oscilloscope trace taken from an experiment in which copper was shock-compressed to 900 kbar. No unusual features are seen. The baseline represents zero resistance, with resistance increasing with vertical trace deflection. The resistance of the unshocked material is constant until the arrival of the shock wave when it

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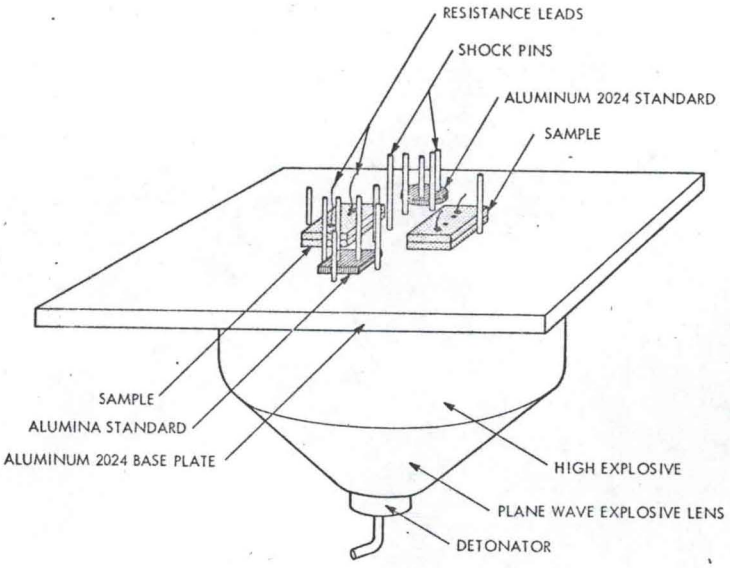


FIG. 1. Experimental configuration.

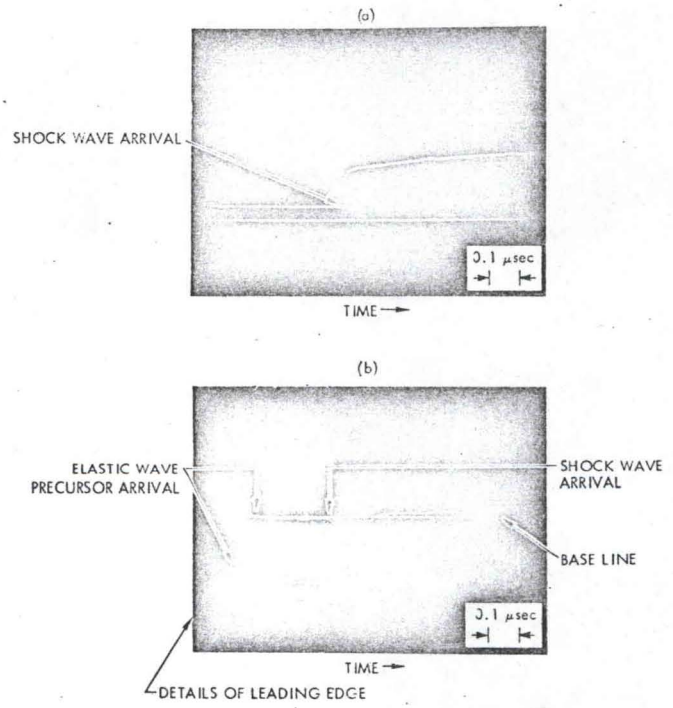


FIG. 2. Conductivity records (a) copper, (b) iron. Insert shows details of leading edge.

abruptly changes to the value characteristic of the shocked copper. The record for iron (Fig. 2b), however, shows surprising structure. To understand this structure, it is necessary to understand the structure of the shock wave propagated through the alumina insulation. Wesgo 995 alumina has a high dynamic yield strength; if it is shocked to pressures between 83 and 700 kbar it will support a two-wave structure. The two-shock-wave system consists of an elastic

compression wave at 83 kbar followed by a plastic shock wave at the system driving pressure. At pressures above 700 kbar, the plastic shock wave overruns the elastic wave, and only the plastic shock is observed. Below 83 kbar, only the elastic wave is observed.

When a 175-kbar shock wave is driven into the alumina–iron sandwich, it separates into an 83-kbar elastic wave and a 175-kbar plastic driving wave. This is the experimental situation recorded in Fig. 2b. Upon arrival of the 83-kbar elastic precursor at the iron foil, the voltage is observed to reverse polarity, corresponding to a negative resistance. The voltage remains slightly negative until the arrival of the 175-kbar wave. At this time a large negative spike is observed, which rapidly decays to a final voltage that corresponds to the resistance of iron at 175 kbar.

The presence of the large negative spike can be explained on the basis of shock-induced demagnetization of the iron sample. The current in the strip has a large magnetic field associated with it. The arrival of the shock wave transforms the iron into the nonmagnetic ϵ-phase, with a corresponding decrease in magnetic susceptibility. The original magnetic field can no longer be supported by the current in the wire; flux diffuses out with a time constant which is related to the skin depth effect and is proportional to the electrical conductivity in the shocked iron. The eddy currents generated by the flux diffusing out of the wire produce the sharp negative spike associated with the arrival of the 175-kbar shock. The pulse height is directly proportional to the difference in susceptibility between the shocked sample and the unshocked one. This experimental record provides striking confirmation of the nonmagnetic nature of ϵ-iron.

The sharp negative pulse was not observed in the 80-kbar shot but was clearly evident in the 175-kbar shot. This is consistent with the previous static and dynamic recovery and Hugoniot measurements which place the α–ϵ transition somewhere between 116 and 130 kbar. Explanation of the negative pulse associated with the precursor is a more difficult question, however. There is a certain amount of demagnetization associated with the shock compression of the α-phase. This would be observed as a small negative pulse decaying to a resistivity characteristic of the compressed α-phase. What is actually observed, however, is an apparently continuous demagnetization of iron at the pressure of the elastic wave, 83 kbar. In the alumina ceramic, when the elastic precursor is driven by a plastic wave of higher amplitude, as in the 175-kbar shot, the elastic wave exhibits a slowly rising ramp structure in pressure, which could cause a continuous demagnetization. To eliminate this as a possibility, an experiment was carried out in which the driving pressures were 80 kbar, at the Hugoniot elastic limit, and 50 kbar. No ramp structure was present, and again, continuous demagnetization was observed. No large negative pulse was found in these experiments.

The results of the conductivity experiments are shown in Fig. 3.[7–10] From these results it

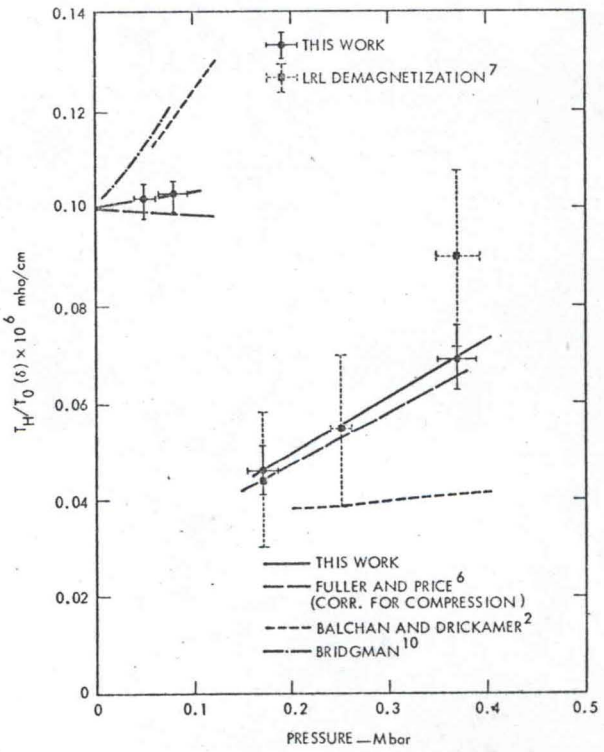


FIG. 3. The electrical conductivity of iron at high pressure (normalized to 25°C).

can be seen that the static and dynamic data

are in good agreement at pressures above 200 kbar. The data of Royce[7] were obtained in demagnetization experiments by a completely independent technique. At 80 kbar and below, there is sharp divergence between the static and dynamic conductivity data. An examination of the equation-of-state data for iron at pressures up to 200 kbar reveals anomalous behavior.[8] There is a definite softening of the Hugoniot as a pressure of 130 kbar is approached from below. This can be partially explained on the basis of recent high-pressure static work in which evidence of some ϵ-phase was found at pressures as low as 100 kbar.[9]

It is obvious that something most unusual is taking place in shock-compressed iron. The indication of a continuous demagnetization at pressures as low as 50 kbar, the divergence in static and dynamically measured resistivities at pressures below 80 kbar, and the anomalous behavior of the Hugoniot of iron at pressures between 50 and 130 kbar are all consistent with a partial phase transition to the nonmagnetic ϵ-phase at pressures as low as 50 kbar. Work on this problem is continuing.

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Электрическая проводимость и демагнитизация в железе были измерены при давлениях до 370 Кбар. Экспериментальные данные с одной стороны подтверждают, что при высоком давлении фаза ϵ в железе не является магнитической, а с другой стороны они также указывают на то, что превращение из фазы α в фазу ϵ может произойти и при низких давлениях около 50 Кбар.