ISENTROPIC COMPRESSION OF IRON WITH THE Z ACCELERATOR

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Abstract. Development of isentropic loading techniques is a long standing goal of the shock physics community. We have used the Sandia Z Accelerator to produce smoothly increasing pressure loading on planar iron specimens over time durations of 100 ns and for pressures to 300 Mbar. Free surface velocity measurements on the rear surface of the continuously loaded specimens were made on specimens 0.5-mm and 0.8-mm thick and clearly show the effects of wave evolution into the well known two-wave structure resulting from the α - ϵ phase transition beginning at 125 kbar. The resulting wave profiles are analyzed with a rate-dependent, phase transition model to extract information on phase transformation kinetics for isentropic compression of iron. Comparison of the experiments and calculations demonstrate the value of isentropic loading for studying phase transition kinetics.

INTRODUCTION

The high-pressure response of iron is important in a number of scientific and technological applications. Iron has been used as a standard material in high-pressure static compression experiments for many years [1]. It has also been a standard for impedance-match shock wave experiments for pressures of almost 100 Mbar. In these experiments, the equation of state (EOS) of an unknown material is determined by measurements of the shock speeds in the iron standard and in the unknown; the EOS of the unknown is determined from impedance matching conditions [2]. Iron is also interesting from a scientific perspective because of the polymorphic phase change which is known to occur under both static and dynamic loading conditions at pressures of about 125 kbar. This transition was first observed in shock wave experiments by Bancroft, Peterson and Minshall in 1957 [3]. Subsequent static high pressure experiments by Jamieson and Lawson [4] and others identified a transition from a bcc phase, referred to as the α phase, which is stable at room temperature and pressure, to a hexagonal close packed phase, referred to as ϵ , at

pressures near 130 kbar. Subsequent studies of iron by several other investigators have confirmed the phase transition and established the importance of phase transition kinetics and strength effects in wave propagation. Barker and Hollenbach [5] provided high fidelity measurements of the phase transition under shock loading using velocity interferometry [6]. This work accurately established the onset of transformation and also effects associated with both the α - ϵ transition and the reverse ϵ - α transition during unloading from high pressure. To describe their data, using an empirical phase change rate equation was used which defined a relaxation time as the difference between the equilibrium and current mass fractions of transformed iron divided by a constant characteristic time. They found this "relaxation time" for transition was in the approximate range of 0.06-0.18 μ s. This work has been subsequently analyzed by several workers.

In this work, we report a new technique for studying phase transitions under dynamic loading. In this method, a magnetic load is applied on the surface of samples of iron using the Sandia pulsed power accelerator, Z [7]. This facility produces a magnetic field in the gap between an anode and cathode and can thus be used to apply a steadily-increasing magnetic pressure to specimens over time intervals of about 100 ns. A ramp wave is thereby produced in the specimen which

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propagates through it and initiates the α - ϵ phase transition during pressurization to 300 kbar. The onset of the transition and evolution into a two-wave structure can be clearly observed through free surface velocity measurements made using optical interferometry. These results have been analyzed with a rate dependent model that provides an estimate of $50 \mu\text{s}^{-1}$ for the peak transition rate at a point on the interior of the specimens, in fair agreement with the results of the Barker & Hollenbach model.

Experimental Technique

Armco iron of 99.8% purity, average grain size of $150 \mu\text{m}$ and average density of 7.85 g/cm^3 was used in these experiments. Two experiments to test feasibility of the technique were performed. In the first, shot Z315, a single iron specimen was magnetically loaded to 300 kbar over 100 ns on Z. The specimen diameter for this experiment was 3-mm and the thickness was $0.5 \mu\text{m}$. In the second experiment, Z329, two specimens of iron were used in this experiment. Specimens of 3-mm diameter and thicknesses of 0.506 and 0.793 mm were prepared from bar stock for use in isentropic loading experiments. The specimens were flat and parallel to less than $5 \mu\text{m}$. The specimens were placed in the anode of the Sandia Z Accelerator in the arrangement shown in Fig. 1. The center of each specimen was 1.385 cm from the center of the anode. In this arrangement, a magnetic pressure is

FIGURE 1. Use of the Z Accelerator for magnetic loading iron specimens. The iron specimens are located in the cathode of the accelerator and are directly exposed to current flowing in the accelerator.

produced at the surface of the specimen of the form

$$P = B^2/2\epsilon_0 = 10^{-7}I^2/2\pi r^2 \quad (\text{in MKS units}), \quad (1)$$

where I is the current and r is the distance from the axis of symmetry. The inset in Fig. 1 illustrates the current history and resulting pressure history applied to the surface of the iron specimens. The radial dependence of the field produces a variation of about 7% in pressure over a lateral dimension

that influenced the wave profile measurements during the reading time of the experiment. The rear surface velocity of the iron specimen was measured with separate VISARs [6], using velocity per fringe sensitivities of 1.053 and 1.057 km/s. The resulting accuracy of the measured free surface velocities was about 0.02 km/s. Each VISAR signal was coupled to the iron specimens with 200- μm diameter radiation hardened fused silica fibers. On each specimen, a fiber placed 0.5 from the free surface illuminated an area of about 300- μm diameter on the polished iron surface and an adjacent 200- μm diameter fiber collected the reflected light. This arrangement produced very high quality fringe signals later.

As discussed later, a large current on the front surface of the iron generates the pressure wave in the present experiments. Because cold iron has a relatively low electrical resistivity, an intense magnetic field penetrates into the iron. Gradients in this pressure enter the momentum equation so the material is subjected to a load distributed over the penetration depth of field, as opposed to just a surface load in traditional shock wave experimentation. At early times, the velocity of magnetic field penetration is supersonic. Thus, in this technique, a elastic precursor can form and not be overdriven for considerable depth. Another distinct feature of this kind of experiment is large heating which occurs near the loading surface. This heating is large enough to cause melting and vaporization which potentially invalidates the assumptions that the material remains in the α or ϵ phase. Our analysis, which is described below shows that the ramp wave forms and propagates away from the to-be-heated region well before the unwanted heating occurs.

The results of shot Z329 are illustrated in Fig. 2, along with numerical simulations, which will be discussed in the next section. The free surface velocity profiles at each of the two thicknesses show an elastic precursor, followed by a plastic wave which loads the material to the onset of transition near 130 kbar. At this point there is a definite slope followed by compression to a plateau region, and then compression to the final pressure. The plateau region is the early stages of the traditional two-wave structure, which is clearly apparent in record for the thick specimen. These results can only be modeled with a rate-dependent transition model, which is described in the next section.

Model

Since iron is dense in the α phase than in the ϵ phase, a single shock is unstable and separates into separate waves that propagate with different velocities. The first of these is the 125 kbar wave that carries the material up to the intersection of the Hugoniot with the phase boundary; the second is the phase-transformation wave that takes the material to the final state in the α phase.

However, Barker and Hollenbach as well as others have demonstrated the α - ϵ phase transformation in iron does not proceed in thermodynamic equilibrium. Rather, for a short time, super-heated α phase persists and the transformation progresses toward the equilibrium α phase in a few 10's of nanoseconds. Whenever experimental dimensions are centimeters and experiment durations are microseconds, these kinetics are not of consequence for interpreting results: wave evolution is over and a two-wave structure is observed. For the present experiments in which specimens are sub-millimeter and experiment durations are only 10's of nanoseconds, these kinetics effects dominate some aspects of wave propagation. In general, when kinetics effects are important the two-wave structure evolves to its final shape rather than forming immediately.

We have modeled two experiments in which account is taken of the non-equilibrium thermodynamics of the iron and the electromagnetic wave interactions governed by Maxwell's equations. All calculations were performed using a modification of a general-purpose, one dimensional, Lagrangian hydrodynamic code. [8] The equations of state for α and ϵ phase iron are those of Andrews [8]. As well, we adopt a generalization [10] of his numerical method [11] which can be summarized as follows. The pressure and temperature at each time and position are advanced using the finite difference form of the following equations

$$\begin{pmatrix} \dot{p} \\ \dot{T} \end{pmatrix} = \begin{pmatrix} a_{s,x}^2 & \frac{K_{s,x}}{V C_{p,x}} \left[\left(\frac{\partial E}{\partial T} \right)_{p,x} \Delta V - \left(\frac{\partial V}{\partial T} \right)_{p,x} \Delta E \right] \\ \frac{\gamma_x T}{\rho} - \frac{K_{s,x}}{V^2 C_{p,x}} \left[\left(\frac{\partial E}{\partial p} \right)_{T,x} \Delta V - \left(\frac{\partial V}{\partial p} \right)_{T,x} \Delta E \right] \end{pmatrix} \begin{pmatrix} \dot{p} \\ \dot{x} \end{pmatrix} \quad (2)$$

Equation (2) is simply a mathematical re-expression of the assumptions that the non-

equilibrium mixture of the α and ϵ phases is locally at uniform pressure and temperature. All thermodynamic quantities are evaluated at fixed mass fraction of the phases (x). Terms have their conventional meaning [10]. In modeling the experiments, Maxwell's equations are solved exactly assuming constant resistivity for iron. These equations were re-formulated to make them compatible with the wave propagation calculations. The magnetic diffusion equation contains an additional term to account flux compression in materials with a non-zero strain rate; gradients in the sum of the mechanical and magnetic pressure are used in the momentum equation; internal energy rises because of mechanical work, joule heating and the work done against the Lorentz force.

At late times, the temperature near the back rises precipitously invalidating the assumption of constant resistivity of the iron. We assume that the measured wave structure has already formed and propagated to the interior of the sample before this occurs. Work is underway to check the validity of this assumption by comparing these results with a mo

FIGURE 2. Comparison of experimental and calculated results.

The method of calculation requires supplying the front surface magnetic field history. We use that measured during the experiment using a B-dot probe. When performing the calculations we found that the B-field from the close in B-Dot probes was incapable of reproducing the results. The second wave was too slow and the calculation peak free surface velocity never achieved the measured value. The best fit was achieved by multiplying the magnetic pressure by a factor of 1.5. (B field larger by $(1.5)^{0.5}$). This change agrees more closely

with a secondary set of B field measurements. Thus, these kinds of shock wave measurements may be valuable as a new electrical/magnetic diagnostic for pulsed-power machines. Figure 2 shows the experimental records compared with several calculations. If transformation times are long compared with experiment duration, the material remains in the α phase. That calculation shows none of the ϵ -wave structure. If the material remains in thermodynamic equilibrium, the two-wave structure is apparent but does not agree with the experimental result. The best match with the experiments occurs when phase-change kinetics is included. A series of such comparisons show that the acceleration behind the first wave is a direct measure of the phase-transformation rate.

There is not a constant rate in our kinetics model. The ramp wave loads the material above 125 kbar and begins to transform the α to the ϵ phase. We did make one detailed comparison. At a depth of 400 μm in the 800 μm specimen, the phase change rate is observed to linearly in time starting at a rate of zero as the stress reaches 125 kbar ($t=122\text{ ns}$) and reaching a maximum rate of $50\text{ }\mu\text{s}^{-1}$ ($t=160\text{ ns}$) when the peak stress is reached at the top of the ramp. The average rate is about $25\text{ }\mu\text{s}^{-1}$ or a phase change time of about 40 ns, which agrees well with the empirical model of Barker & Hollenbach.

Interestingly, some of the wave structure seen in these calculations would not have formed if the ramp wave load had been applied purely through magnetic pressure. Because the penetration velocity of the magnetic wave is supersonic, at early times the structure forms in-depth before the larger amplitudes have a chance to overdrive them.

CONCLUSIONS

The Sandia Z Accelerator has been used to magnetically-load planar iron specimens to pressures of about 300 kbar in time intervals of 100 ns. This loading process produces ramp-waves, which propagate through specimens 0.5 and 0.8 mm thick. This loading process produces continuous pressure loading and induces the α - ϵ phase transition beginning near 130 kbar. The resulting wave profiles are measured with velocity interferometry, which clearly shows the transition kinetics during transformation. The profiles are modeled with a complete two-phase EOS model for iron, that includes the α - ϵ transition. These analyses establish bounds on the kinetic transition times. By analyzing these results we reach

important conclusions on ramp wave experimentation in the Z-environment: (1) whenever magnetic field penetration velocity is supersonic, elastic precursors and other wave features may form which would be overdriven if the load had been applied mechanically. The observation of the elastic precursor puts a lower bound on the magnetic diffusivity of iron; (2) observation of the two wave structure at the rear surface of the iron puts an upper bound as the magnetic diffusivity of iron is only several times its room temperature value. (3) it is likely that the ramp wave propagates out of the highly heated region before joule heating significantly alters EOS properties; (4) the observed rear surface velocities are in compatible with an equilibrium EOS description; Phase change kinetics are important; (5) the rate of phase change agrees well with prior gas gun measurements although a one-to-one comparison is not possible; (6) wave profile measurements may be of significant value as a pulsed-power diagnostic.

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