Ramp compression of iron to 273 GPa

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Multiple thickness Fe foils were ramp compressed over several nanoseconds to pressure conditions relevant to the Earth’s core. Using wave-profile analysis, the sound speed and the stress-density response were determined to a peak longitudinal stress of 273 GPa. The measured stress-density states lie between shock compression and 300-K static data, and are consistent with relatively low temperatures being achieved in these experiments. Phase transitions generally display time-dependent material response and generate a growing shock. We demonstrate for the first time that a low-pressure phase transformation (α-Fe to ε-Fe) can be overdriven by an initial steady shock to avoid both the time-dependent response and the growing shock that has previously limited ramp-wave-loading experiments. In addition, the initial steady shock pre-compresses the Fe and allows different thermodynamic compression paths to be explored.

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I. INTRODUCTION

Both static and dynamic (e.g., shock-loading) methods are used to study materials at high pressures, with the mode of compression determining the pressure-temperature (P-T) path of the experiment. In static studies, the sample can be compressed for hours or longer, and the compression is isothermal. The maximum static pressure yet attained in a diamond anvil cell is ~640 GPa, achieved using nanodiamond micro-balls as second stage anvils. Under shock compression, both temperature and entropy increase; for example, Fe melts at ~225 GPa along the principal Hugoniot (Fig. 1). Dynamic-compression time scales can be extended to tens of nanoseconds or more with ramp-wave loading (RWL); however, resulting in significantly less heating: crystalline materials can thus be studied to pressures of 900 GPa (Refs. 2 and 3) and above. Multiple-wave (shock and/or ramp) loading and static pre-compression likewise reduce the amount of heating relative to a single shock, providing experimental access to conditions found inside planets and very high compressions.

Iron is the dominant constituent of Earth’s core, along with approximately 6–10 wt. % lighter components. Pressures in the core range from 136 GPa at the core-mantle boundary (2891-km depth) to 364 GPa at Earth’s center (6371 km depth), with the crystalline inner core being surrounded by the liquid outer core. While the solid inner core is only 1.6% of Earth’s mass, it exhibits a number of unexplained properties, including elastic anisotropy, hemispherical dichotomy, and radial variability. Solidification of the inner core is expected to help power the geodynamo that generates Earth’s magnetic field in the outer core.

Under compression, iron transforms from the body-centered cubic (bcc, α) phase to a hexagonally close-packed (hcp, ε) phase near 13 GPa (Fig. 1). Most static experiments suggest that the hcp phase remains stable to inner-core pressures, although some experimental and/or theoretical evidence for transformation to other phases has been reported for Fe or Fe-rich alloys at high temperatures. Here, our objective is to provide complementary dynamic-compression measurements on crystalline Fe, extending prior shock experiments to lower temperatures. Iron is reported to melt on the Hugoniot at ~225–243 GPa, so at inner core pressures, shock experiments are probing liquid, not crystalline iron.

In addition to the terrestrial planets of our own solar system, there is significant interest in interior structures of possible extra-solar terrestrial-type planets with up to ~10 Earth masses. Existing models of the interior of extra-solar planets are based on extrapolations of experimental data and theoretical calculations, and better experimental equation of state (EOS) data at multi-megabar (100’s of GPa) pressures are needed to test and improve these models. Ramp-compression experiments are potentially well-suited to this task as they can avoid the melting that occurs in shock experiments on Fe above 225 GPa. Theoretical calculations suggest that Fe will undergo ultra-high pressure transitions to a fcc phase and finally to a body-centered-tetragonal (bct) phase. These transformations are predicted to occur above 2000 GPa and may occur under conditions expected in the deep interior of a 10 Earth-mass terrestrial planet. Theoretical calculations of the melting curve of iron yield a Clapeyron slope steeper than the expected geotherm for a super-Earth exoplanet, which suggests that the likelihood of a molten core decreases as the size of a terrestrial planet increases. Ramp-compression techniques have the potential to provide experimental constraints on planetary properties under such extreme
were measured to be fully dense (7.87 g/cm$^3$) to within a 0.6% tolerance. Metrology of the samples using white-light interferometry determined that the surface roughness was less than 0.30 μm. 

II. EXPERIMENTS

Our ramp-compression experiments were performed at the Omega laser (Laboratory for Laser Energetics) and the National Ignition Facility (NIF). Our targets (Fig. 2) consisted of a stepped iron sample formed by vapor deposition onto a chemical-vapor-deposition (CVD) diamond ablator (Omega: 20-μm thick, 1.5-mm diameter; NIF: 80-μm thick, 3-mm diameter). The iron targets had three steps (four thicknesses) that were formed using a mask which was shifted to a lower bound to the temperature achieved in ambient conditions as additional heating due to plastic work is expected. In order to organize the elastic-plastic behavior, x∈ cubic to hcp phase transition, dynamic fragmentation, and melting in iron. 37–41

FIG. 1. Iron (Fe) phase diagram up to Earth inner core conditions (dashed red box). Solid phase boundaries (x=bcc, y=fcc, ε=hcp) and the melting curve are from Ref. 9. There are uncertainties associated with the melting curve above 100 GPa as well as possible additional solid phases at very high pressures. The orange curve shows a range of possible temperatures for the Earth’s interior.12,68 The pressure-depth scale is obtained from the seismic Preliminary Reference Earth Model.9 The Hugoniot24 (purple curve) crosses the melting curve at ~225-243 GPa. The blue curve shows the temperature rise associated with compression along the principal isentrope. This is a lower bound to the temperature achieved in ramp loading from ambient conditions as additional heating due to plastic work is expected.69 In order to observe the x∈ transition and sample a wider range of P-T states, possible experimental paths showing an initial shock followed by isentropic compression (green and red curves) are also shown. For those paths, the temperature estimates were obtained from the Hugoniot temperature achieved in the initial shock24 and by the temperature rise due to isentropic compression calculated using the Grüniesen parameter and its volume dependence for iron.24

Conditioned. Other recent ramp compression experiments have examined the elastic-plastic behavior, x∈ phase transition, dynamic fragmentation, and melting in iron.37–41

FIG. 2. Target package for ramp compression experiments on iron at (a) Omega and (b) NIF. Laser beams were focused onto the inner walls of a Au hohlraum. The time-dependent laser intensity generates a near-blackbody distribution of x-rays with a characteristic radiation temperature, which increases as a function of time. Ablation of the diamond layer causes a time-dependent compression wave to be launched into the Fe sample. The VISAR velocity interferometer records the temporal history of the free-surface velocity, $u_{fs}(t)$, for each of the four Fe thicknesses.

0.03 μm, thickness gradients were less than 1%, and the step heights were measured to a precision <0.1 μm.

On Omega, the diamond ablator and stepped iron targets were attached to the rear surface of a Au hohlraum (Fig. 2(a)). The hohlraums (General Atomics Corp.) had typical dimensions of 2.5-mm diameter, 2.0-mm length, 25-μm wall thickness, and had a 1.8-mm diameter laser-entrance hole. On NIF, the diamond ablator and stepped iron targets were attached over a 3-mm aperture on the side of a Au hohlraum (Fig. 2(b)). The hohlraum had a diameter of 6 mm, a length of 11 mm, and a laser entrance hole 4.5 mm in diameter and was filled with 0.1 atm. of neopentane (C$_5$H$_{12}$) gas held in by 0.6-μm thick polyimide windows covering the laser entrance hole. Laser irradiation of the Au hohlraum generates a spatially uniform distribution of thermal x-rays with a characteristic radiation temperature, $T_{rad}$, which monotonically increased in time to a peak $T_{rad} \sim 120$ eV (Omega)42 and $T_{rad} \sim 173$ eV (NIF).43 By using a ramped laser drive, a time-dependent radiation temperature is generated within the Au hohlraum. The x-rays produced by the hohlraum ablate the diamond at the target surface and generate a time-dependent, ramp-compression wave propagating through the iron sample.2 Due to the planar inertially confined nature of the ramp drive, our samples are in a state of uniaxial strain. Here, stress and strain are defined
as $\sigma = \sigma_{xx}$ and $d\sigma_{xx} = d\rho/\rho$, respectively, with $x$ being the propagation direction of the compression wave (we take strain to be positive on compression).

Omega is a 60 beam 40 kJ Nd: glass laser system producing frequency-tripled 351-nm radiation.\textsuperscript{46} We designed composite ramped laser-pulse shapes typically using 15 beams, with total laser energy of 2.6–3.3 kJ, over a series of experiments. The laser temporal profile and energy for each beam was measured with a streak camera and a calorimeter. The beams were applied in an azimuthally symmetric geometry at incidence angles of $48^\circ$ and $60^\circ$. Two or three individual temporal pulse shapes were combined to enable us to achieve total pulse lengths ranging from 5–10 ns. The National Ignition Facility is a 192-beam 2-MJ laser\textsuperscript{47} at Lawrence Livermore National Laboratory. In our experiment on Fe, the inner walls of the hohlraum were illuminated with 175 beams of the NIF with a combined energy up to 285 kJ at 351 nm in a 26 ns temporally ramped laser pulse.

A line-imaging VISAR (velocity interferometry system for any reflector)\textsuperscript{48} measured the velocity of the rear free surface, $u_{fs}(t)$, of the stepped Fe target (Fig. 2). The VISAR detects the Doppler shifted of reflected laser light (532 nm (Omega) or 659 nm (NIF)) to record the time history of the surface velocity. Two VISARs with different velocity sensitivities were used to provide redundant data and resolve any ambiguities associated with sharp velocity jumps that exceed the time response of the system. The velocity sensitivity of the interference fringes recorded by the VISAR is controlled by inserting different lengths of fused silica etalons in one leg of the interferometer to alter the optical delay in that leg. On Omega, etalon lengths of 25.2818 and 15.1315 mm produced velocity-per-fringe (VPF) constants of 1.971 and 3.292 km/s. On NIF, etalon lengths of 19.9829 and 11.4366 mm produced VPF constants of 3.1251 and 5.4603 km/s. The VISAR images a 1-mm line across the target onto a streak camera with a temporal resolution of $\pm 0.05$ ns. Fourier analysis of the VISAR interferograms allows resolution of phase shifts to within $\pm 2\%$ of a fringe producing a velocity precision of $\sim 40–60$ m/s. Results from the two independent VISARs were in excellent agreement. The space- and time-resolved thermal emission from the iron free-surface was simultaneously recorded using a streaked optical pyrometer.\textsuperscript{49}

III. RESULTS

A. Refinement of laser drive and target design

Several criteria need to be met to successfully measure the stress-density equation-of-state (EOS) in a ramp-compression experiment.\textsuperscript{50} The target design and laser pulse must be optimized such that shockless compression is achieved over all sample thicknesses. As sound velocities typically increase with pressure, ramp compression waves eventually steepen into a shock front. To avoid this, the step thicknesses are designed to be less than the shock-up distance. In addition, to ensure a common pressure load for all steps, the minimum step thickness needs to be thick enough so as not to allow reverberation of the wave. An initial steady shock common to all step thicknesses can be treated before the onset of ramp compression if the shock state is known. It is essential to provide a spatially planar drive ($\Delta t/t < 0.1\%$) over mm scales, so that each thickness experiences an identical loading history.\textsuperscript{50} The target package must be designed to avoid significant preheat. Our initial set of experiments was carried out to test and optimize these and other components of the experimental design.

Diamond was chosen as the initial ablation surface because its high impedance ensures efficient radiation coupling while its low atomic weight results in high ablation velocities and large-amplitude compression waves. In addition, the large bulk modulus and impedance of diamond makes it resistant to shocking-up and highly efficient at transferring a ramp compression wave into the iron sample. In our experiments, the instantaneous compressive strain-rate varies across the diamond-Fe sample within the $\sim 10^5–10^9$ s$^{-1}$ range. Using EOS tables for diamond\textsuperscript{2} and iron,\textsuperscript{51} an idealized laser pulse shape was designed, which satisfies the above-described criteria for achieving ramp compression. These hydrodynamic simulations assume that (1) there is no rate-dependent material response as the ramp wave compresses the solid target assembly and (2) the EOSs for all constituent materials are correct. There may be significant uncertainties in the EOS tables since the off-Hugoniot compression states were predicted from extrapolation of shock Hugoniot data. Since these experiments are exploring pressure-temperature conditions over compression time scales not previously explored for iron, the design of the experiments is by necessity iterative; after each experiment, the pulse shape was empirically modified to improve the loading and better approach the ideal drive.

To ensure that the thermal evolution of the target is solely due to compressive and concomitant viscous effects, the step portion of the sample cannot be heated by external sources. Possible sources for target preheat include thermal soft x-rays generated from the Au hohlraum, or subsequent diamond ablation; or x-rays from M-band emission from the Au hohlraum at higher energy (2–6 keV). The M-band x-rays can penetrate farther into the target assembly to preheat the sample and are highly intensity dependent. To mitigate the M-band contribution to preheat at Omega, we use 300-μm elliptical phase plates on all beamlines and position individual beams to minimize local intensities on the inner walls of the hohlraum. Radiation hydrodynamic simulations, which give a good match to $T_{rad}$ and $u_{fs}$, show that preheating of the bulk sample from high-energy x-rays in Omega experiments was small (< several hundred Kelvin), and thermal conduction is too slow to affect these results. On NIF, a 10 μm-thick Au layer between the diamond and the Fe (Fig. 2(b)) served to shield the stepped sample from being preheated by radiation from the hohlraum. Detailed radiative-transport simulations confirm the effectiveness of the Au layer, with a predicted temperature rise of only 33 K due to x-ray preheat. No evidence of preheat was observed in the VISAR or streaked optical pyrometer for any of our experiments.

B. Free-surface velocity measurements

Using the above approach for design and optimization, a series of ramp compression experiments were performed on
Fe. Fig. 3(a) shows a representative raw VISAR interferometer record (Omega shot s58588); fringe shifts are proportional to free-surface velocity. Figs. 3(b)–3(d) show the VISAR-extracted Fe free-surface velocity profiles, $u_{fs}(t)$, measured in three experiments. The goal of these experiments was to ramp-compress Fe after it had been precompressed into the high-pressure $\epsilon$-phase by way of an initial steady shock. This shock state represents the initial conditions for subsequent ramp compression. Compression directly to the $\alpha\rightarrow\epsilon$-phase removes the potential complications within the wave-profile analysis of rate-dependence associated with dynamic compression across the $\alpha\rightarrow\epsilon$ phase boundary (see Sec. III C). The ability to control the initial shock state also allows for different regions of pressure-temperature space to be explored (Fig. 1). The longitudinal stress for the $\alpha\rightarrow\epsilon$ transformation in shock compression experiments with 19 mm-thick samples is 12.9 GPa,32 and this is the value encoded in the EOS model used to design the experiments.

The input laser pulse for each experiment is shown as an inset in the figure. In Fig. 3(b), the initial 2-ns portion of the laser pulse shape for Omega shot s58588 was designed to launch a 50-GPa steady shock into the Fe sample, before the onset of subsequent ramp compression. Based on the expected response of Fe, a 50-GPa shock was predicted to compress directly into the $\epsilon$-phase. However, instead of a steady 50-GPa shock ($u_{fs} \sim 2.2$ km/s), we observed a time-dependent steepening in the $u_{fs}(t)$ profiles for thicker steps, implying kinetic hindrance of the $\alpha\rightarrow\epsilon$ phase transition (Fig. 3(b)). In recent work,53 the stress onset for this phase transition was found to be highly rate-dependent at strain rates associated with laser RWL ($\dot{\epsilon} \sim 10^6 - 10^7 s^{-1}$), with values significantly higher than the 12.9 GPa transition pressure traditionally inferred from past experiments. As a result, the 50-GPa shock was insufficient to fully over-drive the transition; the time-dependent nature of the velocity profiles in Fig. 3(b) is thus influenced by phase-transformation kinetics.

To overcome this time dependence, further experiments were designed such that a higher initial shock stress was launched into the stepped Fe sample before subsequent ramp compression. To achieve this, more laser power was applied within the first 2 ns of the pulse (inset of Fig. 3(c)). In this experiment (s58591), a nearly steady shock was successfully generated within the stepped Fe sample in advance of the subsequent ramp compression. In contrast to the $u_{fs}(t)$ profiles in Fig. 3(b), there is a constant rise time associated with the initial shock in Fig. 3(c), consistent with the $\alpha\rightarrow\epsilon$ phase transition being very fast. Based on the measured free surface velocity ($u_{fs} = 3.2$ km/s), and using the Hugoniot equation of state of iron ($U_S$ (km/s) = 3.955 + 1.580u),24 the initial shock pressure is calculated to be 81.6 (± 2.5) GPa ($U_S$ is the shock velocity, and $u$ the particle velocity; here, we assume $u \approx 0.5 u_{fs}$). Figure 3(d) shows the results of a NIF experiment (N120301). In this particular shot, we only examine two steps for a time interval of about 7 ns because the sample shocked up for thicker steps and later times. In this case, we find that the initial shock strength of 65 GPa was sufficient to overdrive the $\alpha\rightarrow\epsilon$ phase transition for these thicker samples. The current results enable us to directly compare the results of shots on NIF and Omega over similar stress ranges. With a modified laser pulse design, future experiments on NIF will be extended to higher pressures and longer loading times.

C. Sound-velocity measurements and stress-density determination

For ramp-wave loading experiments, analysis of free surface velocity histories, $u_{fs}(t)$, from multiple-thickness

FIG. 3. (a) Raw VISAR data from Omega shot s58588. Fringe shifts are proportional to free-surface velocity. (b) Free surface velocity versus time profile for four thicknesses of Fe (shot s58588). The initial 2-ns portion of the laser pulse shape for this shot (shown as inset) was designed to launch a ~50 GPa shock into the Fe sample before the onset of subsequent ramp compression. The thickness of each step is indicated. Light grey bars show agreement between two VISAR channels recording the free surface velocity. The horizontal dashed line indicates the free surface velocity in iron at the equilibrium phase transition pressure of ~13 GPa. The “ramped” plateau at ~3.0 km/s is due to the elastic wave in the diamond shaping the ramp drive applied to the Fe stepped sample. (c) For shot s58591, the laser power in the first 2 ns was increased to generate an ~82 GPa steady initial shock. (d) NIF shot N120301. The first 8 ns of the laser pulse (inset) was designed to launch a steady 65 GPa shock into the multi-step Fe sample.
samples yields continuous stress—density data. We employ an iterative characteristics-based Lagrangian sound-speed analysis technique to correct for wave interactions at the free surface. The analysis\textsuperscript{54–56} assumes (a) a common pressure load history applied to all sample thicknesses, and (b) no time-dependent material response (i.e., simple-wave behavior). Our analysis explores the extent to which deviation from simple-wave behavior (i.e., rate dependence caused by the Fe $\gamma \rightarrow \alpha$ phase transformation) affects the stress-density determination at stresses above those required to complete the transformation. It has been previously noted that, “the correction to the simple wave approximation is comparatively small,”\textsuperscript{54} but the effect on the stress-strain relation far above the time-dependent response has never been quantified. The three shots s58588 (non-simple wave), s58591 (simple wave), and N120301 (simple wave) allow us to directly compare, for the first time, the effect of ignoring the non-simple wave behavior on stress—strain behavior at stresses far above the region of time-dependent response.

In the analysis, stress, $\sigma$, and density, $\rho$, are obtained from the measured wave profiles using the conservation equations for mass and momentum\textsuperscript{54,57–59}

\begin{equation}
\sigma = \rho_0 \int_0^u C_L(u) du,
\end{equation}

\begin{equation}
\rho = \left( \frac{1}{\rho_0} - \frac{1}{\rho_0} \int_0^u \frac{d}{du} \left( \frac{C_L(u)}{C_L(u)} \right) \right)^{-1},
\end{equation}

where $\rho_0$ is initial density of iron, $u$ is particle velocity, and $C_L$ is the Lagrangian sound speed. In order to calculate the bulk values for $u$ and $C_L$ from the $u_{fs}(t)$ profiles in Fig. 3, we follow the iterative Lagrangian characteristics-based analysis method described by Maw and Rothman.\textsuperscript{55,56} $C_L(u)$ is calculated from a linear fit to the corrected stress-wave arrival times as a function of propagation distance at a given $u$. The experimental uncertainties in $C_L(u)$ are propagated linearly to yield uncertainties in stress and density.\textsuperscript{2,50} In previous studies, this analytical approach for extracting stress-density has been applied to ramp compression only. However, an initial steady shock can be treated before the onset of ramp compression if the shock state is known. The free-surface and shock velocities can be uniquely determined through comparison of the experimental wave profiles through several step thicknesses; and the stress-density-energy state of the material can be determined, either directly or by comparison with previous Hugoniot measurements. Ramp compression from this initial state can then be analyzed. We have analyzed shots s58591 and N120301 (steady shock, simple waves) by this method, as well as directly treating the entire compression (including the steady shock which appears as a constant sound speed) using the iterative Lagrangian analysis.

Fig. 4(a) (inset) shows the Lagrangian sound speed, $C_L$, as a function of free surface velocity for the three experiments reported in Fig. 3. For shot s58591, the Fe sample was initially compressed with a shock of $\sim 82$ GPa before ramp compression to 270 GPa (Fig. 3(c)). For shot N120301, the Fe sample was initially compressed with a shock of $\sim 65$ GPa before ramp compression to 240 GPa (Fig. 3(d)). In both

![FIG. 4. (a) Stress versus density for ramp compression shots with or without initial shock. For shot s58591 and N120301, the free surface velocity profiles (Figs. 3(c) and 3(d)) were analyzed in two ways: (1) explicitly treating the initial steady shock (red and blue curves) (2) Assuming ramp compression throughout (orange and light blue curves). The results are nearly identical for the two cases within uncertainties. The grey curve shows the results from shot s58588 (since the designed 50-GPa shock launched in the iron is unsteady for this shot, we did not treat it as an initial steady shock in the analysis). The similarity between the results of shot s58588 and shot s58591 and N120301 above initial shock states implies that the time-dependent response due to the $\gamma \rightarrow \alpha$ phase transition has a small effect on the stress-density state achieved at higher stress levels. Representative uncertainties for the ramp compression data are one standard deviation. The inset shows calculated Lagrangian sound velocities as a function of free surface velocity for the three experiments. The longitudinal and bulk sound speeds\textsuperscript{60} are labeled as yellow and blue solid circles, respectively. (b) Stress versus density for weighted mean of all ramp compression of iron compared with experimental shock data\textsuperscript{60} (solid symbols), nonlinear and high-temperature static data\textsuperscript{61} (open symbols). To obtain the weighted mean stress-density, we averaged all three shots in $C_L$—$u$ space following the procedure described in Ref. 50. For $C_L < 10$ km/s, no averaging was conducted and the values for shot s58588 were taken. For $C_L > 10$ km/s, the weighted mean for all three shots was calculated. The results of these analyses are represented by the black curve. The error bars do not take into account the uncertainty from the Hugoniot initial shock state.](Image 330x298 to 546x746)
cases, the kinetics of the $\alpha \rightarrow \varepsilon$ phase transformation were fast compared to the time resolution of the shot. We have analyzed these wave profiles in two ways: (a) assuming the entire $u_{fs}$ trace is described by ramp compression only (orange and light blue curves); and (b) treating the initial wave as a steady shock followed by a ramp (red and blue curves). The primary differences in the analyses are that for the ramp analysis (a), the initial wave is not considered to be a constant shock velocity and the compression and release are assumed to be reversible (the release wave resembles a release shock rather than a release fan). For the steady shock analysis (b), a constant shock velocity is imposed, and the compression and release are not reversible (the release is along an isentrope assuming a constant Grüneisen parameter and resembles a release fan). These differences are very small and the consistency between these two results indicates that the method of analysis in the shocked region does not greatly affect the calculated densities at higher stresses. The flat $C_L$ response for s58591 in the $u_{fs} = 0-3.2$ km/s range is indicative of the constant shock velocity. Once the ramp commences, the Lagrangian sound velocity increases as a function of $u_{fs}$ (higher levels of stress within the sample). The resulting stress-density states are shown in Fig. 4(a) with the initial-shock Rayleigh line shown by a dashed line up to 82 GPa. Similar analysis is shown for the NIF shot N120301.

Shot s58588 shows time-dependent compression through the $\alpha \rightarrow \varepsilon$ phase transformation causing deviation from a simple wave (Fig. 3(b)). The Lagrangian analysis assuming simple-wave behavior yields a stress-density path shown in Fig. 4(a) by the grey curve. Note that the transition from $\alpha \rightarrow \varepsilon$ phase-like compression occurs at a higher stress than the static data plotted in Fig. 4, consistent with Ref. 53. Shots s58588, s58591, and N120301 represent the first direct comparison of the effect of time-dependent response and time-independent response through a phase transition on the stress-density response derived from simple-wave Lagrangian analysis. We find that in the 82-270 GPa range, the results from these shots show good agreement within experimental uncertainty (using previously developed algorithms).

This result suggests that the time-dependent, non-simple wave response in the $\alpha \rightarrow \varepsilon$ transition region does not significantly affect the stress-density determination at high stress, within the $\varepsilon$ phase. This is the first experimental verification that the correction to the simple wave approximation is small relative to experimental uncertainties following a time-dependent phase transformation.

Figure 4(b) shows the weighted mean (black curve) of all the shots in Fig. 4(a). For RWL of free-surface samples, the maximum temperature cannot be directly determined with standard pyrometric techniques, because the high-stress region lies within the bulk of the sample and hence is inaccessible to optical probes. In our experiments, the initial shock to $\sim$82 GPa is expected to have an associated temperature rise of $\sim$1399 K (Ref. 24) (Fig. 1). A further increase in the temperature during ramp compression will occur due to isentropic compression and plastic-work heating. However, by comparing with the shock compression data (estimated to reach $\sim$5000 K at 220 GPa (Ref. 24)) with static diamond-anvil cell data (at temperatures up to 1250 K), we can infer that temperature along the ramp compression is relatively cool.

D. High strain-rate spall strength measurements

At later times in the measured wave profiles, the free-surface velocity shows a pull-back and ringing that is characteristic of spallation (Fig. 5). Spallation occurs as a result of generation of tensile stresses in the interior of a material due to the interaction of forward and backward propagating release waves near the free surface. The spall strength is defined as the tensile stress in a material that results in dynamic fracture. To estimate the spall strength and corresponding strain rate, we used characteristics-based backward propagation to determine the minimum (negative or tensile) stress state in the sample (e.g., inset of Fig. 6). The strain rate defined as $\dot{\varepsilon} = \frac{\partial n}{\partial t}$, where $V$ is the volume, is calculated in the zone associated with the minimum stress state.

Note that for the $u_{fs}$ profiles analyzed, the free surface reverberation does not interact with the drive before the spall signature. The resulting spall strengths and strain rates from three shots are compared to a previous shock study using high-velocity plate impact in Fig. 6. We observe spall strengths of ramp-loaded iron between 5.6-10.2 GPa at strain rates of 1.0-2.5 $\times$ 10$^7$ s$^{-1}$. Since fracture cannot occur instantaneously, an increasing rate of loading allows for the development of a greater tensile stress in the material before fracture. The spall strength values determined from our RWL experiments are consistent with the expected trend of increasing spall strength with increased strain rate. The thickness of the spall layer behind the free surface is estimated from the characteristics analysis to be 3.8 ($\pm$ 1.2) $\mu$m. This implies an expected oscillation period of $T = 2 \times 3.8$ ($\pm$ 1.2) $\mu$m/C$_{L,0}$ = 1.3 ($\pm$ 0.4) ns, where C$_{L,0}$ is the ambient Lagrangian sound speed (5.8 km/s) at ambient conditions. Within uncertainty, this is consistent with the value of...
FIG. 6. Spall strength versus strain rate. Solid symbols show our results including error bars. Open symbols are previous work.66 The inset is the characteristics plot showing the stress state as a function of Lagrangian position and time for shot s3F388. The arrow points to where the spall occurs (minimum stress state) in the sample. The color bar shows the calculated stress state in the sample.

~1.55 ns observed from our wave profile measurements (Fig. 5).

IV. SUMMARY AND FUTURE DIRECTIONS

We have developed an experimental platform for ramp compression of solid iron to stress levels relevant to the Earth’s deep interior. We report on sound-speed measurements and stress-density determination to a peak stress of 273 GPa. The stress-density results at high stress appear to be insensitive to the details of the analysis regarding the steady shock and the phase-transition kinetics. We demonstrated that initial steady shock compression could be used to avoid the kinetic complications associated with phase transitions and to explore a wider range of pressure-temperature states in the phase diagram. Comparison of three experiments showing simple and non-simple wave response provide direct experimental evidence that the iterative Lagrangian analysis method, with its simple-wave assumptions, provides reliable results for stress and density above the region of time-dependent behavior. More generally, the present study demonstrates that ramp compression can be used to achieve high pressures in solid materials undergoing low-pressure phase transitions. Fig. 1 shows the shock Hugoniot path for Fe as well as examples of initial shocks to different states followed by ramp compression. By using this technique, we can sample a wide range of pressure-temperature space lying between the 300-K isotherm and the shock Hugoniot curve.

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