

# Vanishing dynamic strength measured in a transient high-pressure phase of tin

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This work reports two independent experimental estimations of the dynamic strength of the body-centered tetragonal (bct)  $\gamma$  phase of tin, which occurs at pressures above about 9 GPa and transforms promptly back to the ambient  $\beta$  phase upon pressure release. Measuring strength in such a transient high-pressure phase is challenging. One measurement used free-surface Richtmyer-Meshkov instabilities generated with gas gun impact. Another set of measurements used ramp-release loading in a pulsed-power facility. Strength estimations came from comparison to simulations using a comprehensive multiphase modeling framework that includes equation of state, shear moduli, and strength separately for each phase, and treats mixed-phase regions. Both experimental methods found the  $\gamma$ -phase strength to be very low, within experimental uncertainty of zero. The existing literature on other materials, by contrast, almost universally reports higher strength in transient high-pressure phases compared with ambient phases. Recent Molecular-Dynamics simulations on tin in the literature showed almost zero deviatoric strength during a deformation-induced bct  $\rightarrow$  bct transformation in which one of the  $\gamma$ -phase  $a$  axes “flips” to the  $c$  axis. This reorientation currently provides the most plausible explanation for the low observed strength in  $\gamma$ -phase tin.

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## I. INTRODUCTION

### A. Dynamic multiphase strength

Understanding the strength of materials in extreme conditions is critical for interpreting a wide range of geophysical, planetary, and materials science phenomena. For example, the strength of asteroids at extreme strain rates can have a large influence on the ability to deflect an asteroid via impact [1,2]. For another example, dynamic strength plays a key role in understanding and potentially even suppressing interface instabilities that otherwise reduce the efficiency of inertial confinement fusion (ICF) experiments [3,4].

To further complicate things, the higher pressures or temperatures in, for example, planetary impact processes, mantle convection, and ICF environments can cause the materials to change phase. Asteroids and other extraterrestrial materials are known to undergo solid-solid phase changes under impact conditions [5–8]. In general, materials often transition into complex, off-ambient crystal structures that can exhibit dramatically different mechanical properties, including strength. In some cases, metastable high-pressure phases can be retained upon unloading to ambient pressure [9–13], and strength can then be measured using conventional techniques. More generally, the high-pressure phase is “transient”

because the phase change reverses upon unloading. Measuring strength in that more likely case is much more challenging.

Most of the measurements of strength in high-pressure transient phases have been done in quasistatic Diamond Anvil Cell (DAC) experiments, using standard DAC techniques like Ref. [14]. For example, DAC techniques were used to determine the strength in silicate minerals from the Earth’s mantle after undergoing phase changes that occur between 20 and 35 GPa [15,16]. In metals, the static strength of the omega phase of pure zirconium, which occurs above about 3–6 GPa pressure, depending on the loading triaxiality, has been measured using diffraction methods in a DAC [17,18]. Those measurements reported a significant increase in strength after transitioning to the high-pressure phase. Similar results were found in a Zr-Nb alloy [19]. The most studied high-pressure phase using DAC and related techniques is the  $\epsilon$  phase of iron, which occurs above 13 GPa, because of its relevance to the Earth’s core. The literature reports  $\epsilon$ -phase strengths of about 1–4 GPa depending on conditions [20–23].

Dynamic strength measurements at high pressure are even more challenging because the difficulties in subjecting the material to extreme pressure, often higher than achievable with DAC, often limit putting enough shear on the specimen to sensitively interrogate strength. For dynamic strength,  $\epsilon$ -phase iron is again the most studied transient high-pressure phase. Experiments using Extended x-ray Absorption Fine Structure measurements [24] and Rayleigh–Taylor instability experiments [25–27] showed strengths of tens of GPa, approaching the theoretical strength limit. By contrast, measurements using time-resolved x-ray diffraction under laser shock [28] and pressure-shear plate impact experiments [29] gave strengths of only single-digits in GPa, although still notably higher

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than the ambient phase strength. The conflicting results illustrate the challenges of measuring high-pressure dynamic strength. Rayleigh–Taylor (RT) experiments were also used to investigate the strength of the bcc phase of lead, which occurs above about 50 GPa [30], and they reported a  $\approx 250$ -fold increase in strength over the ambient phase.

Virtually all of the strength measurements referenced above report a significant increase in strength in the high-pressure phase as compared with the ambient-pressure phase.

Ramp release experiments conducted on pulsed power facilities are one technique that has been successfully used to measure dynamic, high-pressure strength in materials [31]. For example, recent work by Brown *et al.* [32,33] used ramp-release experiments to extract the flow strength of tantalum up to 350 GPa. They showed that the tantalum strength increased with pressure at a rate about twice what was predicted by shear modulus scaling [34]. Recent ramp-release experiments on tin reached the transient  $\gamma$  phase that occurs around 9 GPa [35,36]. The analysis of that data looked at phase change behavior, anelasticity, and multiphase strength. Those experiments are reexamined in this work.

Ramp-release and planar shock experiments, the majority of the dynamic experiments referenced above, exercise uniaxial strain deformation, which has a relatively modest ratio of shear (deviatoric) deformation to volumetric deformation. This limits the sensitivity to strength and results in relatively significant uncertainties, i.e., Fig. 9 in Ref. [33] for ramp release. To more sensitively probe strength in extreme conditions, fluid-like instabilities can be used to put more shear into the sample [37]. The RT experiments referenced above fall in that category, but because of the stackup of materials used to generate a ramped pressure drive, they required sophisticated modeling of multiple materials in extreme conditions and then inferencing to quantify strength.

### B. Experimental plan for $\gamma$ -phase tin

Tin, as a post-transition metal with a rich phase diagram showing many crystal structures, is a common test material for studying multiphase behavior [38–42]. In this work, we attempt to assess the strength in the high-pressure  $\gamma$  phase, which has a simple body-centered tetragonal (bct) structure. The experiments all start in the ambient  $\beta$  phase, which has a more complex tetragonal structure, and return to that phase upon pressure release.

Like the aforementioned Rayleigh–Taylor experiments, free-surface Richtmyer–Meshkov Instabilities (RMI), as illustrated in Fig. 1, also use fluid-like instabilities to improve sensitivity to strength. The models required to infer strength from RMI are much simpler, consisting of only one or two materials in well-understood shock Hugoniot and release states. RMI experiments can be fielded in modest laboratory gun facilities, and they can be used to estimate low-pressure strength at strain rates around  $10^7 \text{ s}^{-1}$  [43–47]. An impactor shocks a target with a sinusoidal perturbation on the surface opposite the impact. In this free-surface configuration, the shock causes the perturbations to invert and grow. Strength moderates the growth of the perturbations and, in most experiments designed to measure strength, causes them to arrest. Photon Doppler Velocimetry (PDV) is used to measure the velocity

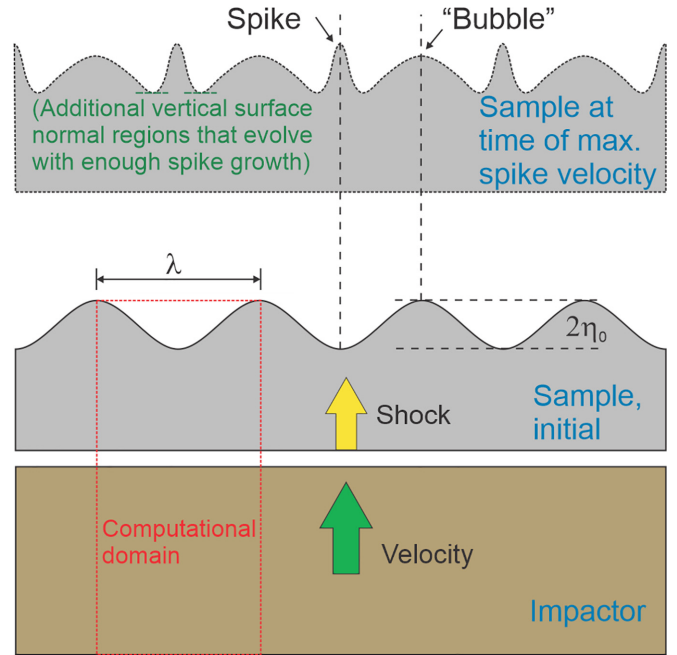


FIG. 1. Richtmyer–Meshkov instability experiments for strength involve a sample with an initial sine wave perturbation being shocked via impact. The original low spots tend to invert to become spikes. The original high spots are called bubbles in the fluids literature, but do not fully invert to low spots in this type of experiment.

of the spike, which is sensitive to strength. Since strength suppresses instability growth, a higher spike velocity implies lower strength and vice versa. The initial size of the perturbation is characterized by the nondimensional amplitude  $\eta_0 k$  where  $\eta_0$  is the sine wave amplitude, and  $k$  is the wave number  $2\pi/\lambda$  where  $\lambda$  is the wavelength. The strain rate in the instability scales linearly with the shock pressure and  $\eta_0 k$  and inversely with the perturbation length scale, taken as  $\lambda$  [Ref. [48], Eq. (3)].

In this work, RMI experiments were fielded on tin at increasing shock pressures, eventually shocking it sufficiently to form the higher pressure  $\gamma$  phase, in an attempt to assess the strength of that transient phase. Previous work has demonstrated that these free-surface RMI experiments, at least when applied without a phase change, are mostly sensitive to strength at relatively low pressure, since much of the deformation occurs after the shock has released off the free surface [49]. Thus, the prospects of measuring significant sensitivity to the  $\gamma$ -phase strength were uncertain, but they were evaluated here by testing and then subsequent analysis.

Additionally, a set of four ramp-release experiments on the same tin and previously reported in Ref. [36] are revisited. The objectives of revisiting these data are twofold: (1) re-analyze the data using identical material models used to interpret the RMI experiments, and (2) focus the analysis on the estimates of  $\gamma$  phase strength rather than the broader range of properties examined originally. These experiments used a magnetic drive to shocklessly compress (i.e., ramp compress) the tin under one-dimensional (1D) uniaxial strain conditions to peak stresses between 17 and 20 GPa. Upon reaching the peak state, the tin was then forced to decompress

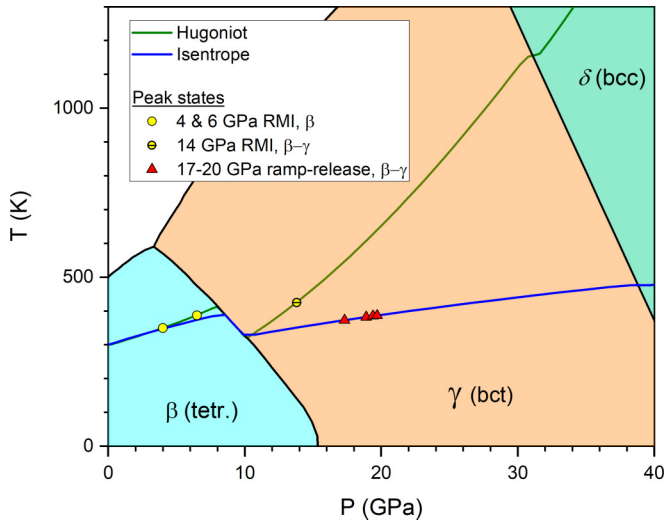


FIG. 2. Peak shock states in the tin experiments overlaid on the SESAME 2163 T-P phase diagram.

(i.e., release), and the pressure drops close to ambient before the strain state becomes multidimensional and the experiment ends. This loading path causes the tin to compress from  $\beta$  to  $\gamma$  on compression and then back from  $\gamma$  to  $\beta$  on release. The sensitivity to  $\gamma$ -phase strength comes from the fact that reversing the direction of the loading while in the  $\gamma$ -phase forces the material to respond in an anelastic manner; various methods can be used to quantify the strength near the peak state [31,36,50].

## II. EXPERIMENTAL METHODS

As an overview, Fig. 2 shows the peak shock states of the RMI and ramp-release experiments in this study plotted over

the tin multiphase SESAME 2163 equation of state (EOS) [51]. Two RMI experiments stayed in the ambient  $\beta$  phase, with peak pressures of 4 and 6 GPa. Those isolate and quantify the ultrahigh-rate strength in the  $\beta$  phase. The third RMI experiment, at 14 GPa, shocked into the  $\gamma$  phase, released back into  $\beta$  phase and showed sensitivity to strength in both phases. The strength in the  $\gamma$  phase was estimated by combining 14 GPa data with the  $\beta$ -phase strength estimates from the 4 and 6 GPa experiments. The ramp-release experiments all experienced load reversal starting from the peak state in the  $\gamma$  phase and were analyzed to estimate the  $\gamma$ -phase strength.

The 14 GPa RMI experiment was specifically designed to isolate  $\gamma$ -phase strength from other effects to the extent possible. The 14 GPa peak state exceeded the phase transition stress by enough margin to (1) overdrive the  $\beta$ - $\gamma$  transition to reduce the complicating effects of phase change kinetics, e.g., [35,36], and (2) spend the maximum amount of time in the  $\gamma$  phase to increase the sensitivity to strength in that phase. A higher-pressure peak state would have risked melting the tin on release because of the combined effects of a higher temperature release path and plastic work heating. Because the release ramps through the  $\gamma$ - $\beta$  reversion, that transition is not overdriven and kinetics might have an effect on the analysis. However, preliminary calculations indicated that this effect would not be large, and an instantaneous reversion could be assumed without significant error. All of these assumptions will be checked later.

### A. RMI sample preparation

Details of the microstructure of the 99.8% pure Sn with  $\approx 80 \mu\text{m}$  grain size used for the targets for this experiment have been reported previously [52]. Figure 3 shows that the target for each experiment included three separate samples, which were 30 mm diameter by 3 mm thick. Each specimen

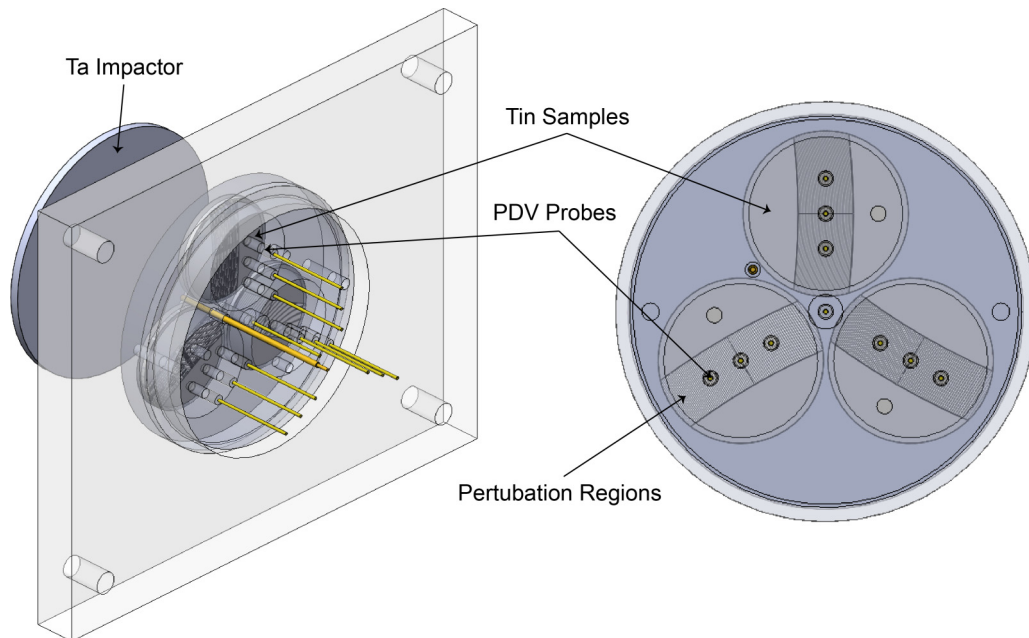


FIG. 3. (left) Isometric model view of the tin RMI strength experiments. (right) Rear model view of the three samples, showing the location of the PDV probes relative to the perturbations. Each sample had one perturbation region with a different  $\eta_0 k$ .

TABLE I. Experimental details of the three RMI experiments. All perturbations have a wavelength of 200  $\mu\text{m}$ .

| Ta Impactor vel. (m/s) | P (GPa) | Phase              | $\eta_0 k$     |
|------------------------|---------|--------------------|----------------|
| 274                    | 4.2     | $\beta$            | 0.4, 0.8, 1.2  |
| 392                    | 6.3     | $\beta$            | 0.3, 0.7, 1.0  |
| 785                    | 13.9    | $\beta$ - $\gamma$ | 0.2, 0.45, 0.7 |

had one perturbation region with a different  $\eta_0 k$ . The perturbation wavelength on all the samples was 200  $\mu\text{m}$ . Based on preliminary calculations,  $\eta_0 k$  values were chosen separately for each specimen to maximize spike growth, but with the instabilities arresting rather than going unstable. Table I shows the  $\eta_0 k$  for each experiment. The width of the perturbation regions is 10 mm, and the cutting radius is 125 mm.

RMI specimens were machined one at a time. A diamond turning air bearing spindle with a balanced fly cutter was set up for this purpose. In this setup, the tools could be changed easily on the fly cutter for the various tools needed. The individual metal pucks were placed on top of the Z-axis tool holder and placed with a custom chuck matched to the diameter of the size of the metal sample. A large-radius diamond tool was used to fly cut the first side to a diamond flat surface. Then the part was flipped in the vacuum chuck and faced down to thickness with the same large-radius tool. The tool was changed to one with the maximum tip radius that could fit inside the sine wave profile and touched off on the surface to set the zero height before machining.

A Zygo white light interferometer was used to measure the peak-to-valley depth and wavelength for each of the perturbation regions. The dimensions for the perturbations were all within 1% of the nominal values. Therefore, nominal values could be used for further analyses with no significant loss of accuracy.

### B. RMI execution

Plate impact experiments were performed on these targets using an 80 mm bore single-stage light gun. This experimental setup is shown in Fig. 3. The samples were bonded into a Lexan plate, 152.4 mm wide by 127 mm high, and 12.7 mm thick, to allow for mounting and alignment in the gas-gun target tank. The impact face of the samples, i.e., the side with no perturbations, was 0.4 mm proud of the Lexan plate. To ensure a planar impact between the projectile and the target, a mirror was affixed to the front of the target, and a laser was used to align a spot down and back along the 9.2 m barrel. With this method, the deviation from parallel at impact is typically sub-milliradian.

The flyer-plates were tantalum, 50 mm diameter by 2.03 mm thick, which were affixed to the front of a Lexan projectile and accelerated to the impact velocity. PDV was then used to measure the velocities in the perturbations using the methodology discussed in previous work [48]. As shown in Fig. 3, three PDV probes were used in each perturbation region to check repeatability. Each sample also had a probe in the flat region to measure the unperturbed free-surface velocity. Table I shows the impact velocities for each experiment

as well as the peak shock stress calculated from the measured velocities in the flat regions.

### C. Ramp-release execution

The experimental methods employed for the ramp-release experiments have been previously published [36] and will only be briefly revisited here. The Thor pulsed power machine [53] was used to deliver a tailored current pulse to an assembly consisting of a nominally 1-mm-thick aluminum (Al) 1100 electrode, 0.6- or 0.8-mm-thick tin (Sn) sample, and 6-mm-thick lithium fluoride (LiF) optical window. The design mitigates any diffusion of the magnetic field into the sample while providing the desired shockless loading and unloading path. The primary diagnostic was a Velocity Interferometer System for Any Reflector (VISAR) [54], providing a measurement of the velocity history at the Sn/LiF interface. On the opposing electrode, an identical configuration is fielded, except the Sn sample is omitted, and so a measurement of the Al/LiF interface is obtained instead. This so-called drive measurement allows for a direct quantification of the applied magnetic field [31,36], which then serves as the boundary condition to run simulations of the sample configuration.

## III. ANALYSIS AND MODELING METHODS

Since there are no closed-form analyses to get strength from measured velocities, interpreting strength from an RMI or ramp-release experiment requires comparing simulations to the data. This section first covers the overall multiphase modeling approach used to simulate phase strength effects for both types of experiments. Next, it discusses the experimental metric for RMI used to compare data to simulations, which is a variation on past literature. Then, it goes over the details of the RMI simulations. Finally, the details of the ramp-release simulations and interpretation are summarized.

### A. Phase-strength scaling in a multiphase model

In previous work, a simulation comparison to data could be used to determine a representative average strength for a given experiment, see, e.g., Refs. [45,55]. Because our experiments are sensitive to strengths in both the  $\beta$  and  $\gamma$  phases in a single experiment, we instead build an analysis around scaling individual phase strength models in the Common Model of Multiphase Strength and Equation of State, or CMMP [56]. This will allow us to eventually incorporate the experiments into a broader suite of experiments on tin and compare strength estimates in spite of differing conditions of strain rate, temperature, and pressure.

The CMMP is a comprehensive multiphase modeling framework that includes equation of state (EOS), phase-change kinetics, shear moduli, and strength separately for each phase, and deals with mixed-phase regions [56]. Here, we review just one key equation relevant to this work. Although an arbitrarily sophisticated strength model for each phase can be accommodated in the CMMP framework, a simpler option is available for cases where limited data preclude the full calibration of a comprehensive model [57]. That limitation applies here, where simple constitutive testing is not possible for the high-pressure  $\gamma$  phase. Thus, the flow stress

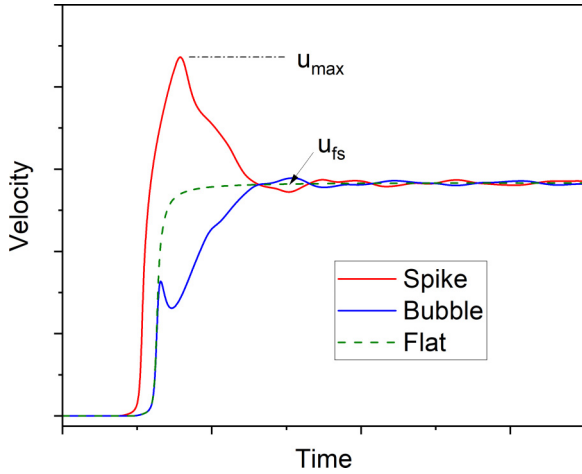


FIG. 4. In a typical RMI experiment for strength, the spike and bubble move with different velocities as the instability shape evolves like in Fig. 1. In the case shown here, where the instability arrests, they later come together to the free-surface velocity,  $u_{fs}$ , that would be seen in a flat region. The maximum spike velocity  $u_{max}$  and the ratio  $u_{max}/u_{fs}$  are strength-sensitive measures of the spike growth.

for the difficult-to-access  $\gamma$  phase is based on a scale factor  $\chi_\gamma$  applied to the strength model for the ambient  $\beta$  phase, but using the shear modulus for the  $\gamma$  phase:

$$Y_\gamma = \chi_\gamma \hat{Y}_\beta(\epsilon_{p,\gamma}, \dot{\epsilon}_p, \hat{G}_\gamma(\rho_\gamma, T), T, P). \quad (3.1)$$

The shear modulus swap comes from the common assumption of scaling strength by the shear modulus, although recent work calls into question the scaling at more extreme pressures [34,58].

We start with the extensively calibrated foundation for a tin multiphase model, including a Preston–Tonks–Wallace (PTW) strength model [59] calibrated for the  $\beta$  phase [52]. However, even the calibrated  $\beta$ -phase model may not be accurate here because we are extrapolating from the calibration regime for that model, up to about  $4000 \text{ s}^{-1}$  [52], to strain rates around  $10^7 \text{ s}^{-1}$  in the RMI experiments. Thus, we also apply a scale factor  $\chi_\beta$  to the  $\beta$ -phase flow stress.

Therefore, our strength estimation from the RMI and ramp-release experiments is reduced to finding scale factors for each phase,  $\chi_\beta$  and  $\chi_\gamma$ .

### B. RMI experimental metric for strength assessment

In this work, we make a small change to the model comparison to data traditionally used to assess strength. For reference, Fig. 4 illustrates typical RMI velocities measured by the PDV probes on the perturbation regions and flat region in Fig. 3. In previous work, we used the maximum spike velocity,  $u_{max}$ , as the experimental metric compared with simulation results to assess the strength. The maximum spike velocity is very sensitive to strength and comes early enough in time to not be affected by tensile damage [55]. Thus, the strength estimation is isolated from any confounding effects of damage. Here, instead, we use the ratio  $u_{max}/u_{fs}$  from the PDV measurements as the comparison metric. Normalizing by  $u_{fs}$ , the free-surface velocity, reduces the uncertainty in the strength estimation caused by the uncertainty in the impact velocity and inaccuracy

in the EOS [49], because the ratio changes more slowly than just  $u_{max}$  with such errors. Also, using the ratio better isolates material strength from small changes to the shock Hugoniot caused by deviatoric strength. We emphasize that to take advantage of this improvement, the simulations that provide  $u_{fs}$  must be repeated for each variation in strength magnitude.

Velocity-time spectrograms were produced from the PDV oscilloscope waveforms using the Fast Fourier Transform-based (FFT-based) SIRHEN software [60]. The surfaces that are oriented normal to the PDV laser tend to return significantly more light, so the spike tip tends to return a distinct and easily identified signal. In cases where the signal-to-noise ratio was poor or the signal dropped out for short periods of time, the expected shape of the spike velocity curve (see Fig. 4) was used to help identify the maximum. Because of this heuristic process, conservative estimates of uncertainties were assigned individually for each PDV probe based on the quality of each signal and any ambiguities in identifying the maximum.

### C. RMI simulations

The RMI experiments were modeled using FLAG, an arbitrary Lagrangian-Eulerian, explicit, finite-volume hydrodynamics code using arbitrary polyhedral computational zones [61–64]. No mesh relaxation or Eulerian remapping was used in these calculations because all the deformations were modest in the time of interest. The computations used a two-dimensional plane strain mesh on a cross section through the perturbation, using the  $1-\lambda$  domain shown in Fig. 1, with symmetry boundary conditions on the lateral edges, which effectively assumes infinitely repeating perturbations. The Ta impactors were initialized with the experimentally measured velocities from Table I and then impacted the target through a contact surface. The calculations used a classic VonNeumann and Richtmyer viscosity with a quadratic coefficient of 1.2 and a linear coefficient of 0.15 [65]. Numerical viscosity artificially reduces the predicted spike velocities [66], but the effect converges away [55], so the strength estimates used peak spike velocities from meshes with zone sizes of  $\lambda/40$ ,  $\lambda/80$ , and  $\lambda/160$ , and then a linear best fit of those values extrapolated to a zero zone size.

FLAG conserves energy. Therefore, 100% of plastic work is converted to heat, i.e., the Taylor–Quinney coefficient is 1.0. Much recent attention has been paid to studying the conversion of work to heat in metals [67], with some relatively low values reported but often with inconsistent results [68,69]. Recent work on tin reported that the cumulative Taylor–Quinney coefficient in dynamic testing exceeds about 0.85 for strains above 20% [70], hopefully minimizing effects from our assuming 1.0.

The tantalum impactors were modeled using an extensively calibrated model for tantalum [33], including the 93524 SESAME equation of state [71] and a PTW strength model.<sup>1</sup>

<sup>1</sup>The PTW parameters for Ta were the “PTW-calibrated” fit from Ref. [33] and are given in Table III of Ref. [72] as “Tri-lab.”

As mentioned above, the tin was modeled using an extensively calibrated CMMP model including phase-specific shear moduli, the “sn06” calibration of the PTW strength model for the  $\beta$  phase [52], and the 2163 SESAME EOS [51]. Calculations for all  $\eta_0 k$  and the flat regions were repeated for a range of values of the strength scale factors for each phase,  $\chi_\beta$  and  $\chi_\gamma$ . The resulting  $u_{\max}/u_{\text{fs}}$  values were then compared with the experimental results to estimate those scale factors.

#### D. Ramp-release simulations

The ramp-release experiments were modeled in the ALE-GRa multiphysics code [73] to account for the magnetic nature of the loading condition. The change in codes is not expected to be relevant when comparing with the RMI results since, as in previous studies [33], the CMMP model implementations were verified across both codes. The ramp-release simulations were modeled in 1D as fully Lagrangian with the magnetic field being applied as a boundary condition to the Al electrode. A  $1\ \mu\text{m}$  mesh was utilized across the electrode and sample, which then linearly graded out to  $5\ \mu\text{m}$  at the rear of the LiF window. Since these simulations do not contain a shock, the treatment of artificial viscosity is much less important than for the RMI simulations, but the same formulation and coefficients were used for consistency. The simulated velocity profiles are believed to be fully converged with these settings. The Al and LiF were treated as standards with the materials models the same as described in Ref. [31], while the Sn was modeled using the same CMMP implementation and parametrization described in the previous section for the RMI simulations. In addition, an anelastic model [74] was included to account for the Bauschinger-like reversal effects typical of these types of release experiments. Anelasticity is discussed further in Sec. IV D.

### IV. RESULTS AND DISCUSSION

#### A. RMI experimental results

Each experiment resulted in 11 velocity spectrograms—one for each of the three PDV probes on each of the three perturbation regions and two probes on flat regions. The only exception was one probe at  $\eta_0 k = 1.0$  on the 6 GPa experiment saturated the detector and did not give usable data. We present just a few spectrograms that best illustrate the important features in the data. Figures 5 and 6 from the lower-pressure experiments that stayed in the  $\beta$  phase share several common features described below. An elastic precursor precedes the main shock. Two distinct shock arrivals are evident, one each at the low spot and high spot of the perturbations in Fig. 1. In principle, the region in between would also be seen by the PDV probe, but not enough light is returned to the probe by those angled surfaces to be evident in the spectrogram. The first shock arrival corresponds to the spike, and the velocity rapidly rises to a maximum before decaying back to the bulk free-surface velocity. The second shock arrival corresponds to the bubble, and its velocity peaks at a significantly lower value, drops to a minimum, and then rises up to the bulk free-surface velocity. It is during this time with distinctly different velocities that the shape of the instability evolves. Within

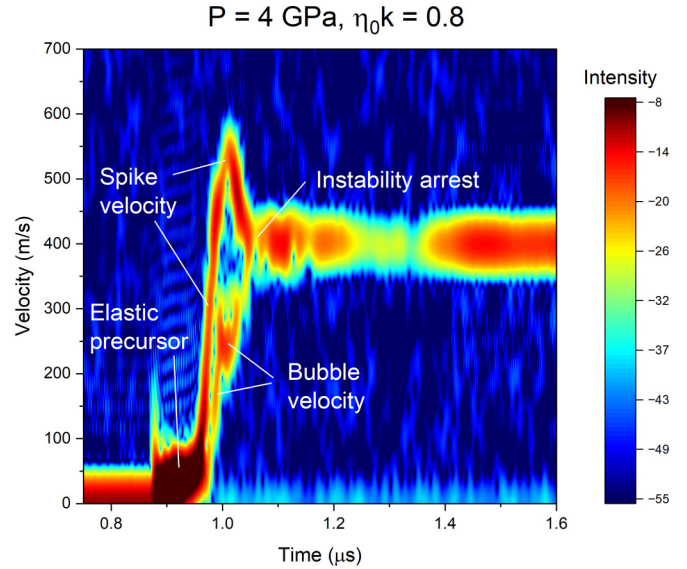


FIG. 5. A  $\eta_0 k = 0.8$  PDV spectrogram from the 4 GPa experiment in the  $\beta$  phase shows the classic features of RMI growth and arrest.

about  $0.2\ \mu\text{s}$ , the velocities come back together, indicating the instability has arrested from strength effects.

Figure 7 shows a PDV spectrogram from the 14 GPa  $\beta$ - $\gamma$  experiment for  $\eta_0 k = 0.45$ , the intermediate perturbation size. The elastic precursor is still evident. There is no additional feature during the shock rise, indicating that the  $\beta$ - $\gamma$  phase change is overdriven. The spike and bubble velocities are distinct and eventually come together, indicating instability arrest. A third distinct velocity signal is evident between those of the spike and bubble. Because of the strong intensity of that signal, some people have mistaken similar signals for the spike velocity. Figure 1 shows that, for large enough perturbation growth, a third region with a vertical surface normal

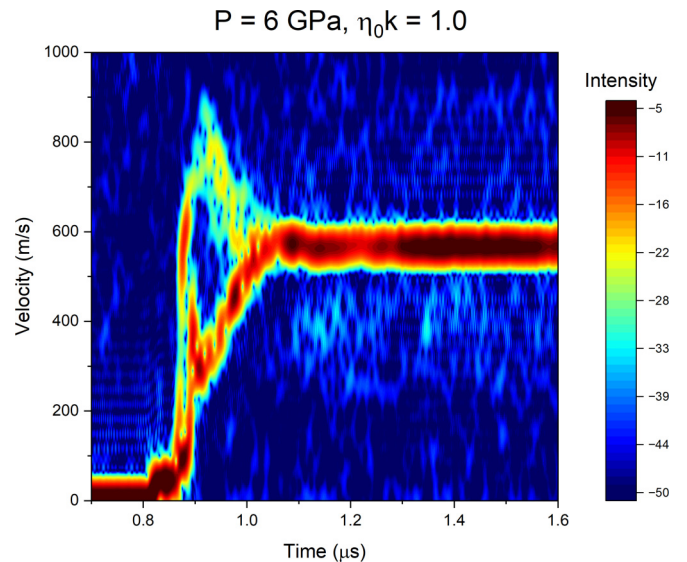


FIG. 6. An  $\eta_0 k = 1.0$  PDV spectrogram from the 6 GPa experiment in the  $\beta$  phase shows similar features just at higher velocities.

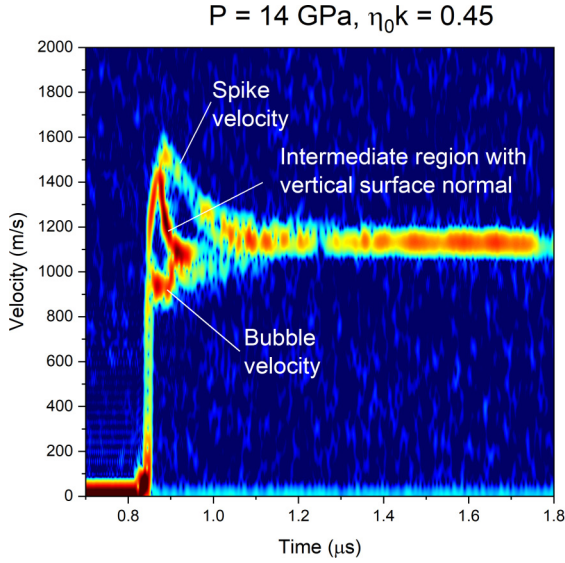


FIG. 7. An  $\eta_0 k = 0.45$  PDV spectrogram from the 14 GPa  $\beta$ - $\gamma$  experiment shows an overdriven phase change and features a strong velocity signal from a third region with a vertical surface normal (shown in Fig. 1). Otherwise, it shows the expected features of RMI growth and arrest.

develops. Because that region is concave upward, it tends to focus the reflected light and give a stronger signal than the spike.

The 14 GPa PDV spectrogram in Fig. 8 for the larger  $\eta_0 k = 0.7$  perturbation shows different behavior. The signal for the spike velocity does not return to the free-surface velocity but rather plateaus at an increased velocity. This indicates that the spike tip has broken off. This phenomenon is sometimes referred to as a jet or as ejecta. The fairly distinct single veloc-

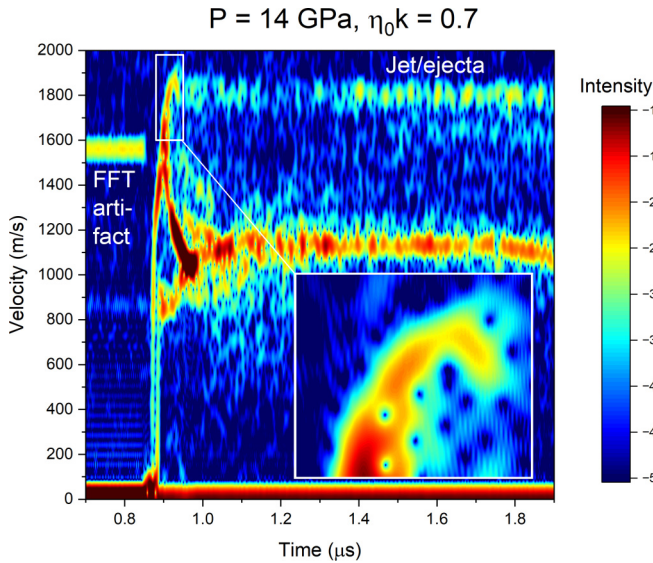


FIG. 8. An  $\eta_0 k = 0.7$  PDV spectrogram from the 14 GPa  $\beta$ - $\gamma$  experiment shows that the tip of the spike has broken off, resulting in a jet or ejecta. The inset shows that the spike velocity started to pull back from the maximum before breaking off, which means the data are still useful for strength estimation.

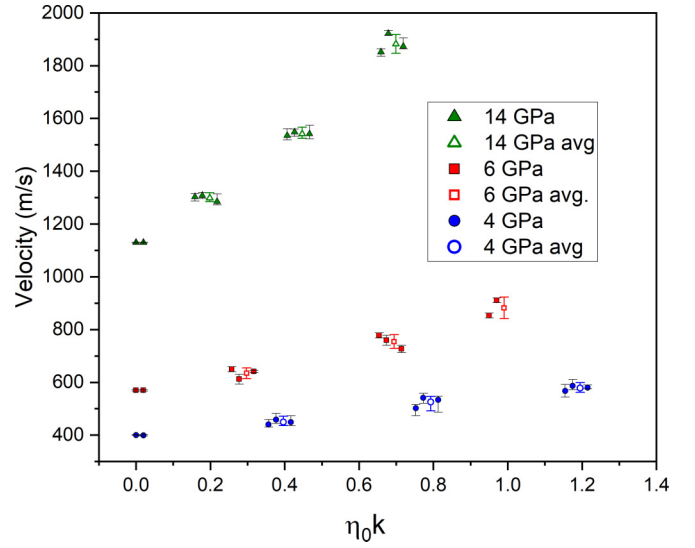


FIG. 9. Maximum spike velocities extracted from the PDV spectrograms. The  $\eta_0 k$  are offset so the points do not obscure each other.  $\eta_0 k = 0$  points are taken on flat regions of the target.

ity for the ejecta is consistent with solid ejecta, as compared with a more continuous velocity spectrum that is often seen for liquid ejecta, like Fig. 14 in Ref. [75].

If the perturbation is too unstable, the maximum velocity does not provide useful information about the strength. Fortunately, as shown in the inset in Fig. 8, the spike velocity reaches a maximum velocity and starts to decrease before the spike tip breaks off. That turnaround in velocity is an effect of strength, and the maximum spike velocity can usually still be used for estimating strength. Although the turnaround is a short transient, the strength of that signal in Fig. 8 is well above the noise background levels. Similar behavior with a turnaround in the velocity was seen in the other two PDV probes on that  $\eta_0 k = 0.7$  perturbation, further confirming the observation.

Figure 9 shows the maximum spike velocities extracted for all three experiments. Values for each probe and then an average are offset slightly in  $\eta_0 k$  for visibility in the plot. The data show the expected trends of increasing maximum velocity with increasing  $\eta_0 k$ . The three probes on each perturbation region agree within their individual uncertainties with more than the 68% frequency expected for one standard deviation uncertainties. As discussed in Sec. IV.H in Ref. [48], the separate probes function similarly to repeat measurements, and such agreement supports the argument that grain-scale heterogeneity does not have a significant effect on the results. A possibly notable case where the three probes measuring a single perturbation do not quite repeat within uncertainty is  $\eta_0 k = 0.7$  at 14 GPa, the perturbation that went unstable. The increased scatter there probably reflects the stochastic nature of the instability process.

Figure 10 shows the  $u_{\max}/u_{fs}$  values calculated from the velocities in Fig. 9 using the average values and associated uncertainties. The trends are smooth, and the significant spike growth indicated by velocities up to 67% above  $u_{fs}$  should provide good sensitivity to strength. Table II gives the numbers from Figs. 9 and 10. The  $u_{fs}$  values are more precise

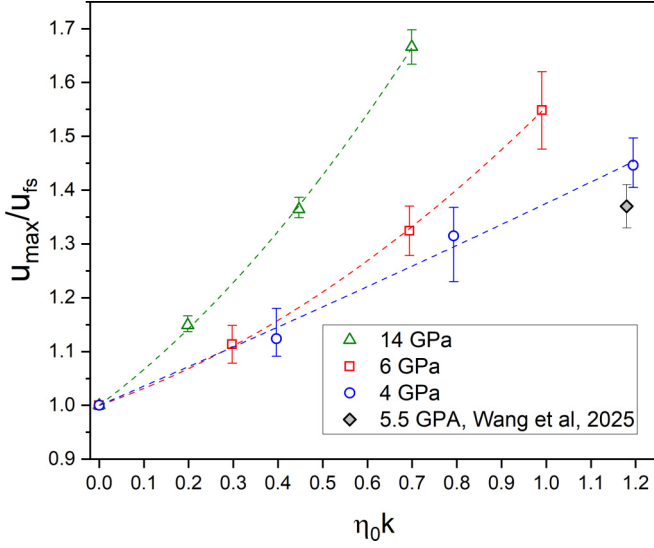


FIG. 10. Maximum spike velocities relative to free-surface velocities, taken from the average values and uncertainties from Fig. 9. Second-order polynomial fits are shown to guide the eye. A data point from similar testing in the literature does not fall within the trends.

because the steady postshock velocities allow a much longer time window in the FFT analysis.

Figure 10 also shows the data point from a recently reported independent RMI experiment on tin at 5.5 GPa [76]. The velocity is significantly lower than what would be expected for an interpolation between our 4 and 6 GPa experiments. Further information, such as the purity and pedigree of the tin in and details of the velocity measurements in Ref. [76], would be required for us to hypothesize as to the reason for the difference.

### B. Model check

Velocities measured in the flat regions, which are less sensitive to strength, provide a good check of other parts of the model, notably the EOSs of the tin and the tantalum impactor. Before proceeding, the flat regions were simulated

TABLE II. Average velocities from Fig. 9 and relative velocities from Fig. 10.

| P (GPa) | $\eta_0 k$ | $u_{\max}$ (m/s)       | $u_{\max}/u_{fs}$       |
|---------|------------|------------------------|-------------------------|
| 4       | 0.0        | $399.7 \pm 1.9$        | 1.0                     |
|         | 0.4        | $449.3 + 22.3 - 13.0$  | $1.124 + 0.056 - 0.033$ |
|         | 0.8        | $525.5 + 21.1 - 33.9$  | $1.315 + 0.053 - 0.085$ |
|         | 1.2        | $578.1 + 20.0 - 16.3$  | $1.446 + 0.05 - 0.041$  |
| 6       | 0.0        | $569.6 \pm 2.4$        | 1.0                     |
|         | 0.3        | $634.2 \pm 19.8$       | $1.113 \pm 0.035$       |
|         | 0.7        | $754.4 \pm 25.9$       | $1.324 \pm 0.046$       |
|         | 1.0        | $881.9 \pm 40.8$       | $1.548 \pm 0.072$       |
| 14      | 0.0        | $1130.0 \pm 1.2 - 1.8$ | 1.0                     |
|         | 0.2        | $1298.4 + 19.6 - 13.8$ | $1.149 + 0.017 - 0.012$ |
|         | 0.45       | $1541.6 + 25.2 - 17.4$ | $1.364 + 0.022 - 0.016$ |
|         | 0.7        | $1882.6 \pm 36.1$      | $1.666 \pm 0.032$       |

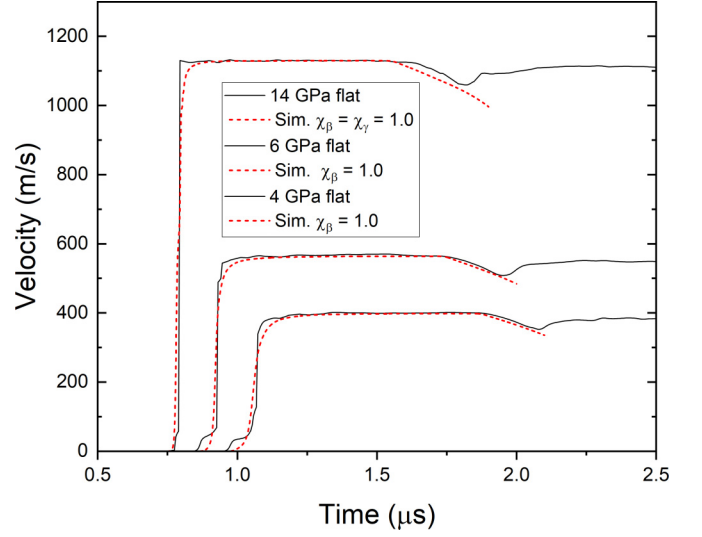


FIG. 11. Multiphase model simulations of velocities on the flat regions of each RMI experiment using scale factors of 1.0 for beta and gamma strength agree acceptably with the data, giving confidence in the model. Times were adjusted to synchronize the data to the simulation and to separate the curves for visibility. Since there is no damage model, the comparison ends when the data show a spall pullback.

with nominal scale factors of 1.0 on the strength in the two phases. Figure 11 shows the resulting good agreement with the measured velocities, especially the important peak state represented by the sustained, maximum velocity. Interestingly, the release wave for only the 14 GPa experiment arrives notably too soon in the simulation, suggesting an inaccuracy in the  $\gamma$ -phase sound speed. Overall, the agreement is more than good enough to proceed. After calibrating the strength scale factors, we recheck this comparison.

### C. RMI $\beta$ -phase strength

For the 4 and 6 GPa experiments, Fig. 12 shows the simulated  $u_{\max}/u_{fs}$  values for different values of  $\chi_\beta$  compared with the experimental results. Within uncertainty, the simulations capture the trends in  $u_{\max}/u_{fs}$  vs  $\eta_0 k$ , which gives confidence in the modeling. The best fit and associated uncertainties were determined by interpolation as  $\chi_\beta = 0.59 \pm 0.06$  to best match the 4 GPa experiment and  $0.70 \pm 0.05$  to match the 6 GPa experiment. For several of the simulations with higher strength and smaller  $\eta_0 k$ , Fig. 12 shows  $u_{\max}/u_{fs} = 1.0$ , implying strength has completely suppressed the spike growth. In some of those cases, there is some spike growth in the simulations, but the peak in  $u_{\max}$  is still below  $u_{fs}$ .

To help interpret these scale factors, we re-analyzed the data using the traditional approach of finding a constant strength that best matches the data [45,55]. Next, the strain rate corresponding to the strength estimate was determined using the Physical Regime Sensitivity (PRS) analysis [49,77,78]. For the 4 GPa experiment, the strength was estimated at  $500 \pm 60$  MPa at  $6.6 \times 10^6 \text{ s}^{-1}$  and for the 6 GPa experiment  $660 \pm 60$  MPa at  $8.5 \times 10^6 \text{ s}^{-1}$ . Figure 13 compares these strength estimates with the PTW model and some of the constitutive data used for calibration. The plotted

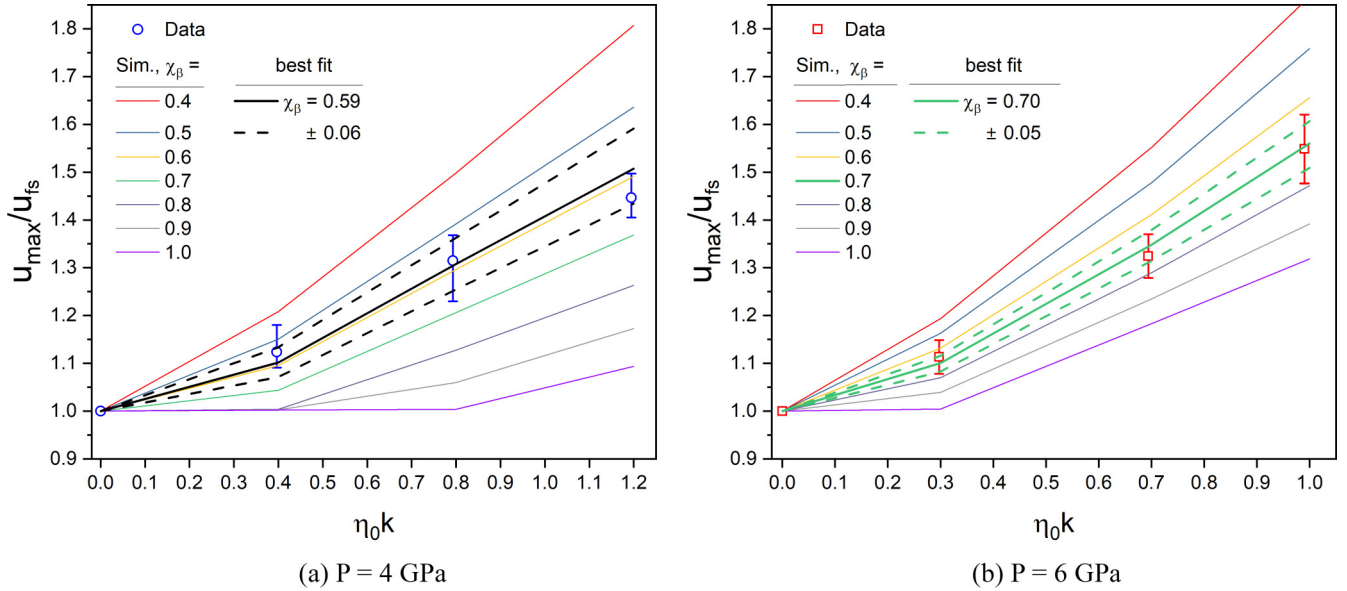


FIG. 12. Comparing simulations with data gives a strength scale factor on  $\beta$ -phase strength of (a)  $0.59 \pm 0.06$  to best match the 4 GPa experiment and (b)  $0.70 \pm 0.05$  for the 6 GPa experiment.

calibration data just for the tests starting at room temperature is taken from Ref. [52] at 20% strain. Based on extensive PRS analysis using simulations that match measured velocities, 20% strain is a reasonable comparison point with RMI estimates [49]. The strength from the PTW model is also extracted at 20% strain and includes thermal heating from plastic work. The PTW extrapolation from the calibration constitutive data to the RMI strain rates is modestly too strong for the RMI strength estimates. A new PTW fit that incorporates RMI data is planned for future work. For now, we proceed with the current PTW fit and use a scale factor to get more realistic  $\beta$ -phase strength at RMI strain rates.

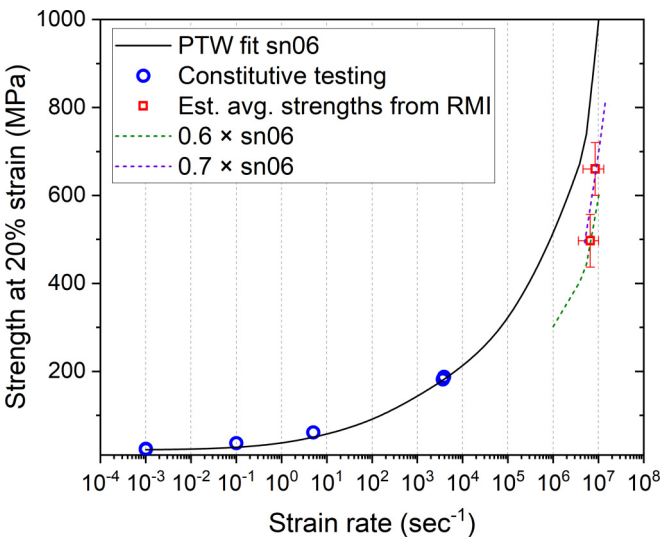


FIG. 13. The extrapolation of the sn06 PTW fit from the calibration regime to the RMI strain rates was too strong. The scale factors on sn06 used to fit the 4 and 6 GPa RMI data are consistent with the average strengths estimated for those experiments.

The results in Fig. 13 have another valuable implication. Experiments like RMI do not give a simple stress-strain curve and, as a result, are usually harder to use for strength-model calibration. In Fig. 13, the PTW fits scaled by the calibrated scale factors pass through the simple average strength estimates. The agreement indicates that the inverse should be true: an average strength estimate combined with a Physical Regime Sensitivity analysis to establish the strain rate, etc., can give a calibration point that could be used with simple model calibration routines. In other words, a PTW model fit that passes through the RMI strength points in Fig. 13 should reproduce the maximum spike velocity data. Such a calibration approach would be much simpler than techniques that require intensive simulations of the experiment, see, e.g., Ref. [79]. This observation is only demonstrated for RMI experiments. RMI experiments are sensitive to relatively narrow ranges of strain rate [49,78], which likely makes them more amenable to this approach than experiments with broader sensitivities like some Rayleigh–Taylor strength experiments [78].

#### D. $\beta$ -phase detwinning anelasticity

$\beta$ -phase tin with its complex body-centered tetragonal multilattice is susceptible to twinning and detwinning at dynamic rates [52,80–82] or low temperatures [83,84]. Upon load reversal, detwinning can result in Bauschinger-like anelastic effects on strength. Recent work looked at tin experiments on four experimental platforms that access extreme strain rates, where a simple analysis of strength is not possible, so a material model is part of the interpretation [85]. The platforms included Taylor cylinder [86–89], dynamic hole closure [72,90,91], ramp-release, and RMI. (The RMI experiments reported briefly in that work are the 4 and 6 GPa experiments reported here, although no detail was given there.) In a compelling result, they found it necessary to add a model of twinning and detwinning to make the model-based strength

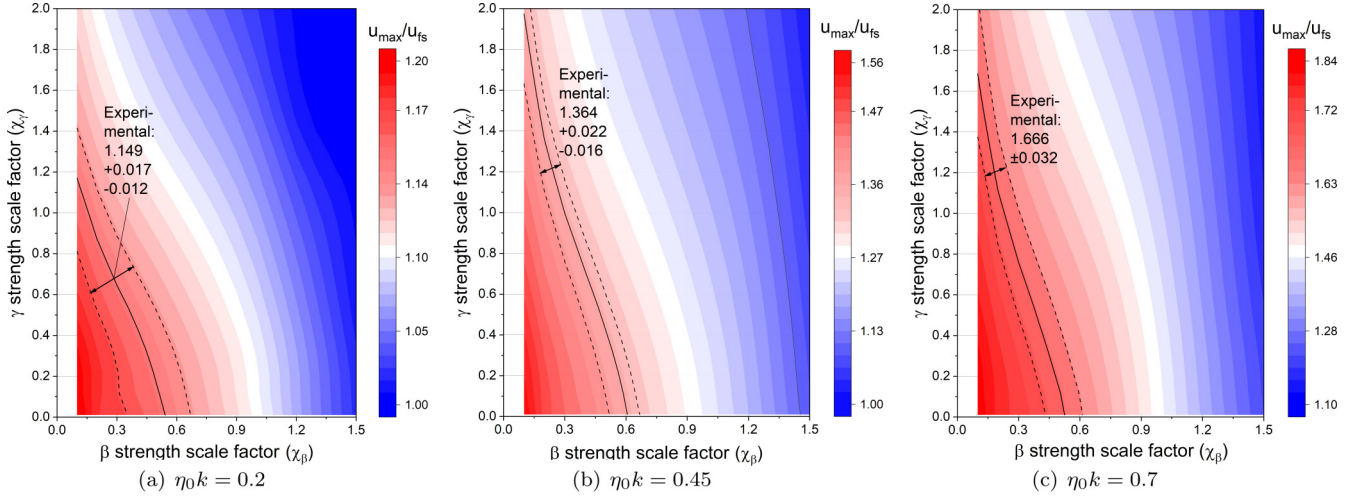


FIG. 14. The maximum spike velocity in the 14 GPa RMI experiment is sensitive to strength in both the  $\beta$  and  $\gamma$  phases. The experimentally observed velocities and uncertainties are also shown, thus indicating the region of two-phase strength solutions that match the data.

estimates from all platforms consistent with each other. They found ramp release and hole closure to have the largest reversal or detwinning effects, but RMI was affected as well.

When the twinning effects were added separately onto a standard dislocation-based strength model, the nontwinning strength estimated from RMI was significantly higher than what we report here for beta phase strength (compare [85] Fig. 4 to our Fig. 13). In the absence of an explicit model of twinning in our RMI interpretation, anelastic reversal effects are here implicitly included in the scaling of the PTW strength model. In other words, the scaled model gives an average strength that includes the anelastic effects. From a predictive modeling standpoint, such simple scaling would not account for apparent strength differences from different loading paths that resulted in different amounts of twinning and detwinning. Therefore, an explicit twinning model would be more versatile in the long term. Loading path consideration are important and can easily complicate simple comparisons of strength [92].

### E. RMI $\gamma$ -phase strength

Figure 14 shows the results of the simulations used to assess the  $\gamma$ -phase strength from the 14 GPa RMI experiment. The figure also indicates where the experimental results fall. First, we explain and discuss the calculational results. Each plot, one for each  $\eta_0 k$ , represents a two-dimensional (2D) matrix of calculations with differing strength scale factors in each phase. The map is colored by maximum spike velocity relative to the free-surface velocity. In general, increasing the strength in either phase, i.e., moving to the right or top of the plot, suppresses the instability and reduces the velocity. The axes are scaled the same in both directions (they cover a different range, so the areas are not square), allowing us to use the slope of the contour lines to make some observations. If the sensitivities to the scale factor for each phase were equal, the contour lines would be at  $45^\circ$ . In all cases, the lines are closer to vertical, indicating that they are more sensitive to the  $\beta$ -phase strength. That is not surprising, since the free-surface release means the spike is in the  $\gamma$  phase for only a

short time. However, the sensitivity to the  $\gamma$ -phase scale factor is large enough to make the experiment useful for calibration of strength in the off-ambient, transient  $\gamma$  phase.

The experimentally observed velocities, including uncertainties from Table II, are bounded by dashed contour lines in Fig. 14. Thus, until we use further information, any combination of strengths bounded by the dashed lines will match the data within uncertainty. The  $u_{\max}/u_{fs}$  uncertainties for the three  $\eta_0 k$  are roughly the same percentage-wise, ranging from 1% to 2%. Thus, we can observe that the wider uncertainty-bounded region for  $\eta_0 k = 0.2$  indicates that it is less sensitive to strength, which matches RMI expectations that it will not have enough spike growth to optimize sensitivity.

Now we constrain the  $\beta$ -phase strength factor to 0.53–0.75 per the results in Sec. IV C, shown as a region bounded by vertical lines in Fig. 15. The intersections of these regions with the experimental regions are colored in cyan. The cyan region is now the smaller region of possible strength solutions that simultaneously match both sets of experiments. The vertical extent of the cyan region gives the possible solutions for the  $\gamma$ -phase strength factor.

All values of  $\chi_\gamma$  in the cyan regions are not equally likely. The tips of the cyan regions represent single values of spike velocity and  $\chi_\beta$  at the bounds of their respective uncertainties. As one moves down in  $\chi_\gamma$ , the cyan region gets wider, indicating a broader set of possible solutions. Those solutions also move closer to the midpoint (more likely value) of the distributions for velocity and  $\chi_\beta$ . Thus, the width of the cyan region at any given  $\chi_\gamma$  is proportional to the likelihood of that  $\chi_\gamma$ .

Considering the width of the cyan regions, the most likely value of  $\chi_\gamma$  is 0.0, with a distribution that falls off as  $\chi_\gamma$  increases. The best representation of this is  $\chi_\gamma = 0.0 + 0.24 - 0.0$ , with the uncertainty value chosen to encompass about 68% of possible solutions, as one standard deviation uncertainty bars should. One might ask if this could be fairly represented as  $0.12 \pm 0.12$ , but that would imply 0.12 as the most likely value with the likelihood falling off on either side, which is not the case here. One could abstractly interpret the

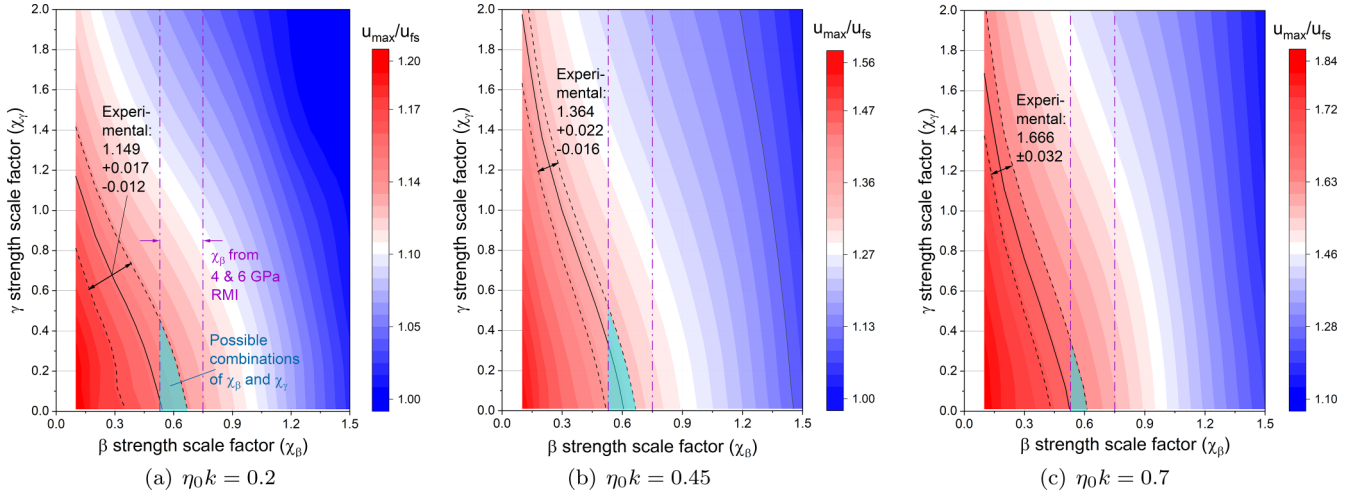


FIG. 15. Constraining the  $\beta$ -phase strength factor per the results in Sec. IV C to the region bounded by the purple dot-dash lines, the cyan-shaded regions now show the combinations of strength factors for each phase that simultaneously match the RMI experiments at all three pressures. The conclusion is that the  $\gamma$ -phase strength is low, with  $\chi_\gamma$  estimated as  $0.0 + 0.24 - 0.0$ .

other half of a more symmetric distribution as occurring at negative  $\chi_\gamma$ , but negative strengths are not physically allowed, thus cutting off that half.

Regardless of the details, the  $\gamma$ -phase strength appears to be low, within the uncertainty of no strength.

The solutions would be more satisfying (i.e., better agree with the individual experiments) if the centerlines of the two regions intersected, but they do not. Lower strength seems to be required in one or both phases. Later, we discuss possible explanations for this.

#### F. Ramp-release $\gamma$ -phase strength

Figure 2 shows that the RMI and ramp-release experiments follow different paths and assess strength at somewhat different temperatures and strain rates (strains are comparable). Since the PTW strength model includes thermal softening and strain rate hardening, comparing in terms of the  $\gamma$ -phase strength scale factor,  $\chi_\gamma$ , implicitly provides a correction for these differences and thus a reasonable comparison.

A summary of two nominal simulation sets for the ramp-release experiments is given in Fig. 16, where only  $\chi_\gamma$  is altered, from near 0 to 1. The  $\beta$ - $\gamma$  (forward transition) and  $\gamma$ - $\beta$  (phase reversion) kinetic parameters,  $\beta$ -phase strength scaling factor, and anelastic parameters were determined from a global Bayesian calibration, similar to that described in Ref. [36] but using a more modern calibration method [93] and enforcing the modeling consistency with RMI described in Sec. III D. The finer details of this parameter set are not particularly important to this discussion, rather what is noteworthy is the simulations represent a good overall match to the experimental data such that there is confidence the EOS and kinetics are accurate and the  $\gamma$ -phase strength parameters can be inferred with minimal bias.

As was found in previous work [36] and will be shown later, there is a strong correlation between the strength and the anelasticity in the release region of the simulations, which makes them difficult to disentangle. The simulations in Fig. 16 represent a moderate amount of anelasticity, which is defined

by producing the correct qualitative nature of the wave profile (i.e., it does not have an elastic-perfectly plastic character) without it overwhelming the material strength.

As illustrated, altering  $\chi_\gamma$  over the interval  $[0,1]$  with this fixed set of anelastic parameters has a sizable effect on the nature of the simulated velocity profile near the peak and in the unloading region, reflecting the sensitivity to strength and the intent of the experimental design. One can immediately see that a low value of  $\chi_\gamma$  is more consistent with the data than a value of 1. Thus, as in the RMI analysis, these experiments suggest that the  $\gamma$ -phase strength is low.

However, we caution that this result can be misleading because more anelasticity permits larger strengths while maintaining consistency with the data. Thus, Fig. 16 should be viewed as a reasonable baseline, but more sophisticated methods are required to fully interpret the experiments.

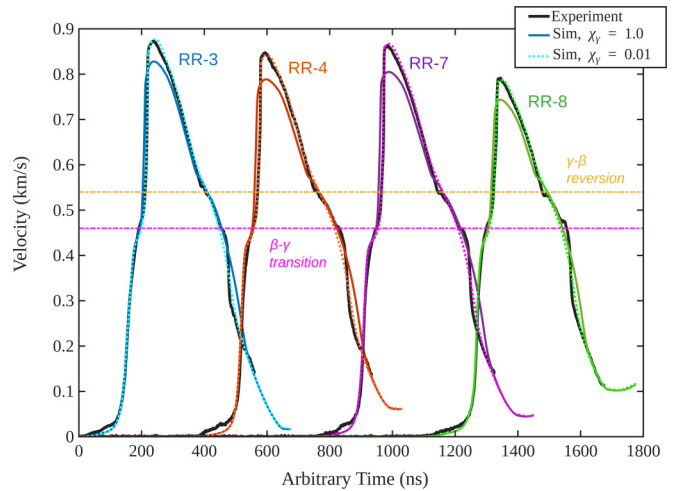


FIG. 16. Baseline simulations of the ramp-release experiments with a fixed amount of moderate anelasticity suggest a low  $\gamma$ -phase strength. The more rigorous analysis in Figs. 17 and 18 provide quantitative estimates for  $\chi_\gamma$ .

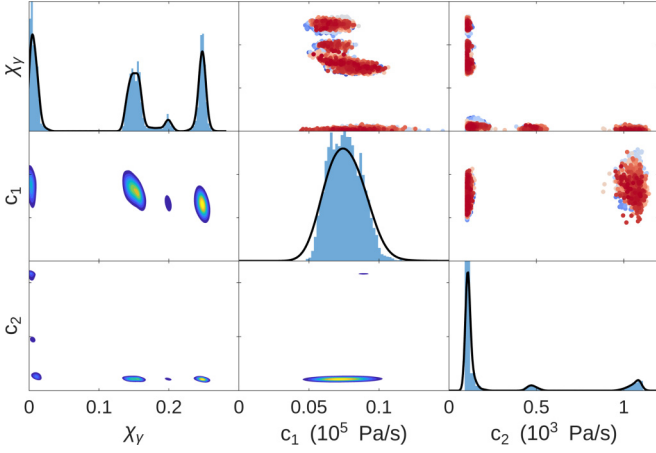


FIG. 17. Pairwise plot and marginal densities for the posterior distribution of the 3  $\gamma$ -phase strength parameters calibrated against the ramp-release measurements.

To better quantify  $\chi_\gamma$ , Bayesian calibration was performed using the latest approach developed for experiments of this type [93]. However, as in previous work [36], when calibrating over all uncertain parameters and the entire velocity history, it was found that there are strong correlations between the broader CMMP parameter set (i.e., strength, kinetics, and anelasticity). This introduces identifiability issues and questions about potential biases in the inference. As an alternative approach, the present study utilizes a calibration that isolates the  $\gamma$ -phase strength parameters of interest over the velocity regime it is known to be most sensitive to, similar to the method successfully employed previously for a variety of metals using the same platform [50]. As highlighted by Fig. 16, the velocities can be isolated to the unloading region from the peak state to near the phase reversion since this is the region most sensitive to the  $\gamma$ -phase strength. Additionally, the calibration examined only the most relevant tin materials parameters:  $\chi_\gamma$  and the anelastic parameters denoted by  $c_1$  and  $c_2$ .

The results of the calibration are summarized in Fig. 17. This pair plot represents the posterior probability distributions for each parameter along the diagonal and the 2D marginal distributions for pairs of parameters on the lower diagonals. The upper diagonals are the values in the Markov chain colored by the chain number and may be viewed as diagnostic, demonstrating good mixing and convergence of the solution. The results are highly multimodal, suggesting the calibration had difficulty identifying a distinct combination of  $\gamma$ -phase strength and anelasticity consistent with the data.

Instead, three distinct modes appear to be present: very low  $\chi_\gamma \approx 0.01$  coupled with low anelasticity,  $\chi_\gamma \approx 0.15$  coupled with larger anelasticity, and  $\chi_\gamma \approx 0.25$  coupled with significant anelasticity.

The overall conclusion from the calibration is that these data are not sufficient to decouple the strong correlations between strength and anelasticity. However, all solutions are encompassed by  $\chi_\gamma < 0.3$ , and so the initial claim of a low  $\gamma$ -phase strength, within uncertainty of zero consistent with the RMI results, still holds through this more rigorous analysis. It is difficult to further quantify such a complex distribution,

but taking a simple mean and standard deviation as a gross representation gives  $\chi_\gamma = 0.13 \pm 0.1$ .

Figure 18 zooms in on the velocities in the peak and subsequent release region to show the prediction intervals resulting from the calibration. The gray lines represent the training data, given by 6000 simulations sampling across six uncertain parameters. The uncertain parameters include the experimental uncertainties (boundary condition scaling of 0.4% and electrode and sample thickness errors of 3  $\mu\text{m}$ ) along with the CMMP parameter variations sampled over the uniform intervals  $\gamma_\chi \sim U(0, 1)$ ,  $c_1 \approx U(0.01, 1.0) \times 10^5 \text{ Pa/s}$ ,  $c_2 \approx U(0.1, 10.0) \times 10^3 \text{ Pa/s}$ . The coverage of these simulations fully span the experimental measurements, and the strength and anelastic intervals were selected based on simulations like those in Fig. 16 to encompass all reasonable scenarios. The blue prediction intervals represent the reduction in uncertainty through the calibration process, and the excellent match to the data suggests the model forms and their posterior probability distributions represent the data well.

It is particularly interesting how tight these intervals are considering the disparity in the three modes identified in the posterior distributions in Fig. 17. This further suggests that there is not a unique combination of anelastic and strength parameters that best fit the data, rather they offset each other to provide equally valid and excellent matches to the data.

The simulations can be used to extract the characteristic metrics shown in Table III. The peak stress falls between 17 and 20 GPa, and the corresponding volumetric strains are  $\approx 0.2$ ; peak plastic strains are closer to 0.15. Due to the nature of the shockless compression, the temperatures remain relatively low, with the simulated values coming in between 430–470 K. There is a surprisingly small difference in the simulated heating between  $\chi_\gamma = 0$  and  $\chi_\gamma = 1$ . Although even a value of  $\chi_\gamma = 1$  results in only a moderate strength ( $Y \approx 1.5 \text{ GPa}$ ) at these conditions so perhaps minimal plastic work heating should be expected. The strain rates are the most difficult to quantify because the rate has more spatial variation and depends on how the applied stress wave evolves through the Sn sample. At the Al/Sn interface (i.e., sample input) the loading rate is  $\approx 8 \times 10^5 \text{ s}^{-1}$  while the unloading rate is  $\approx 6 \times 10^5 \text{ s}^{-1}$ . As the wave evolves through the sample, the loading rate increases while the unloading rate decreases. At the Sn/LiF measurement interface (i.e., sample output), the loading rate increases to the  $10^6$ – $10^7 \text{ s}^{-1}$  range, with the higher rates associated with the steepening due to the phase transformation, while the unloading rate is relatively uniform at  $\approx 4 \times 10^5 \text{ s}^{-1}$ . The strain rate believed to be most relevant to the  $\gamma$ -phase strength inference is the unloading rate, for which an average of  $5 \times 10^5 \text{ s}^{-1}$  is reported.

### G. $\gamma$ -phase lattice-reorientation softening

Recent work provides a plausible explanation for the low strength we observed in the  $\gamma$  phase [94]. Molecular Dynamics (MD) simulations using a spectral neighbor analysis potential (SNAP) looked at high-rate compression of  $\gamma$ -tin along both the short  $c$  axis and a long  $a$  axis of a single crystal. Loading along the  $c$  axis showed simple elastic-plastic strength behavior. However, loading along the longer  $a$  axis after first entering the  $\gamma$  phase showed almost zero deviatoric

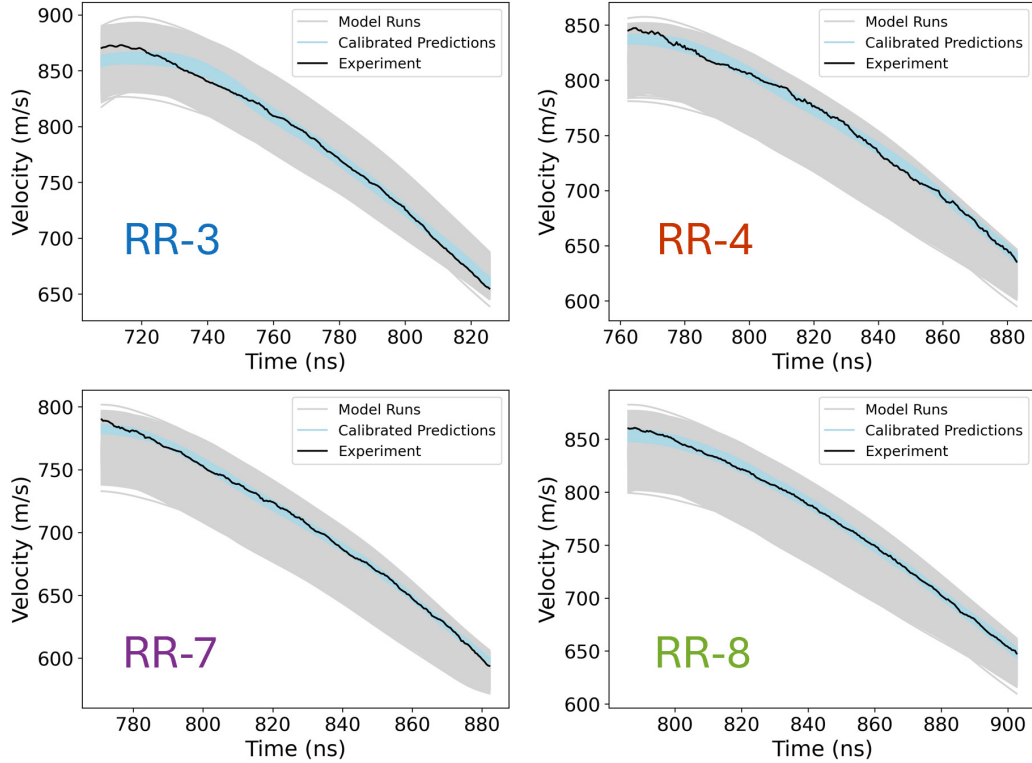


FIG. 18. Release velocity region for the four ramp-release experiments compared against the entirety of the simulation data along with the calibrated predictions. Despite the probability distributions being highly multimodal (see Fig. 17), the combinations of different parameter sets produce similar solutions, resulting in a tight predictive interval in excellent agreement with the data.

strength up to a strain of about 12% during a  $bct \rightarrow bct$  transformation in which one of the  $a$  axes “flips” to the  $c$  axis. After exhausting the flipping reorientation, the strength returned to a significant magnitude. Although like twinning, this distinct mechanism does not entail shear along any particular direction and does not have an invariant crystallographic plane [94]. The researchers expected that under different loading conditions, twinning is also likely to be a major mode of inelastic deformation in  $\gamma$  tin. Additional work would be needed to fully quantify these effects for polycrystal samples, but the mechanisms should be active in appropriately oriented grains.

From the simulations of our 14 GPa RMI experiment, the strain accumulation in the spike tip while in the  $\gamma$  phase does not exceed about 10%. The ramp-release experiments exercise similarly modest plastic strain in the  $\gamma$  phase. Thus, the  $bct \rightarrow bct$  flip provides a plausible explanation for the observed low strength.

TABLE III. Summary of the Ramp-Release (RR) experiments.

| Expt. | Sn thickness (mm) | Peak stress (GPa) | Peak strain | Average unloading strain rate ( $s^{-1}$ ) |
|-------|-------------------|-------------------|-------------|--------------------------------------------|
| RR-3  | 0.6085            | 19.7              | 0.206       | $5 \times 10^5$                            |
| RR-4  | 0.8010            | 18.9              | 0.201       | $5 \times 10^5$                            |
| RR-7  | 0.6233            | 17.3              | 0.191       | $5 \times 10^5$                            |
| RR-8  | 0.7953            | 19.4              | 0.205       | $5 \times 10^5$                            |

Testing for the return of strength at higher strains would further confirm the MD prediction. To increase strain in the  $\gamma$  phase, one could use a tamper on the RMI perturbations to sustain pressure longer [95–100]. That should also increase the overall sensitivity to  $\gamma$ -phase strength. However, the experimental complexity increases.

#### H. Recheck model

The simulations for Fig. 11 were repeated with the new strength scale factors. Figure 19 shows that the strength reductions have improved the match with the experimental velocities in the flat regions. The release wave in the 14 GPa experiment now arrives at the correct time, presumably from the reduction in  $\gamma$ -phase strength, reducing the sound speed. Also, the shock steepness and rounding at the peak of the shock, both strength effects, better capture the data for all three experiments. Note that these were 1D calculations with a highly refined mesh (2  $\mu m$ ) to fully resolve those features here and for Fig. 11. The elastic precursor in the lower-pressure  $\beta$ -phase experiments is underpredicted by the models. The precursor represents the initial yield strength, i.e., 0% plastic strain. Previous work in other materials has shown that the elastic precursor can be inconsistent with strengths determined at finite plastic strains [33].

#### I. Reversion kinetics assumption

All of the preceding RMI analysis assumed equilibrium phase fractions, i.e., instantaneous phase changes. The sharp,

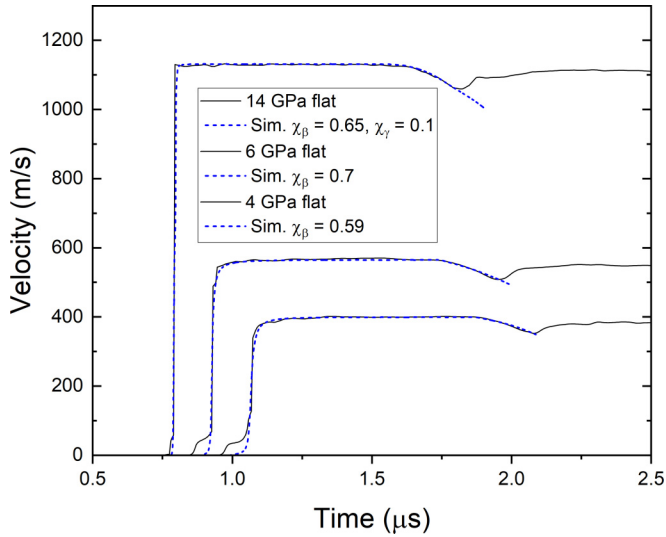


FIG. 19. Compare with Fig. 11. Reducing the strength using the calibrated scale factors improved the agreement of multiphase model simulations with the data in the flat regions. Notably, reducing the gamma phase strength reduced the sound speed and improved the timing of the release wave in the 14 GPa experiment.

uninterrupted shock rise for the 14 GPa experiment in Figs. 7, 8, 11, and 19 shows that the  $\beta$ - $\gamma$  forward transition was indeed overdriven and effectively instantaneous. However, since the release ramps rather than shocks across the reverse transition, the equilibrium assumption is less justified. We recently measured the  $\beta$ - $\gamma$  transition in both directions using impact testing and are preparing that for publication. A preliminary fit of the Greeff kinetics model [101] to data for the  $\gamma$ - $\beta$  reversion from a test releasing from 14.5 GPa gave a  $\beta$  parameter of  $2.0 \times 10^{-5} \mu\text{s}^{-1}$  and  $\kappa = v/\beta$ , which governs the initial behavior of the phase transition, of  $5000 \text{ Mbar cm}^3 \text{ g}^{-1}$ . Simulations for  $\eta_0 k = 0.45$  in the 14 GPa RMI experiment were run with these kinetics parameters and compared with simulations with an instantaneous transition. The maximum spike velocity with kinetics increased by about 5 m/s or 0.3%. That corresponds to a very small uncertainty in  $\beta$ -phase strength, equivalent to  $\pm 0.02$  in  $\chi_\beta$ . Considering the more modest sensitivity to  $\gamma$ -phase strength in Fig. 14(b), 0.3% difference in velocity corresponds to something like  $\pm 0.09$  in  $\chi_\gamma$ . While modestly significant, this potential error does not change the conclusion that the  $\gamma$ -phase strength is quite low.

#### J. RMI melting and mixed solid-liquid

Because of the low melting temperature of tin, see Fig. 2, partial melting is a concern in just a few perturbation regions of the RMI experiments. For uniaxial-strain impact loading, the onset of melt on release is reported to result from a shock of about 19.5 GPa [102], above the shock pressures here. However, plastic work from the large shear strains in the spike region of the RMI experiments will locally raise the temperature. The larger  $\eta_0 k$  reach the highest temperatures because of larger plastic strains. Figure 20 shows a simulation of the 14 GPa experiment with the largest  $\eta_0 k$ , 0.7, using the calibrated strength settings. The mass fraction of liquid

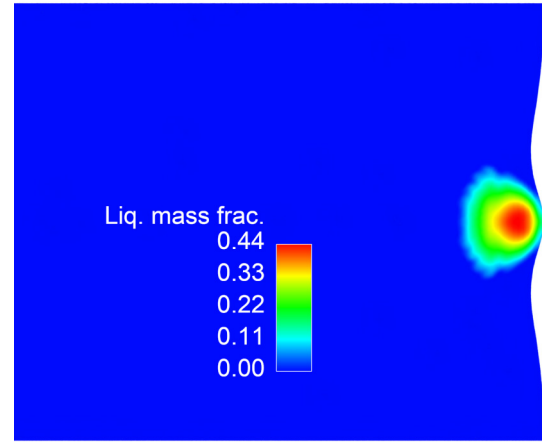


FIG. 20. At the time of the maximum spike velocity, the liquid mass fraction in the most highly deformed region of the spike is about 44% because of plastic work heating, with the remainder in the  $\beta$  phase. Because the multiphase model averages strength across all phases, the region still has some strength and the spike arrests. Shown for  $\eta_0 k = 0.7$  in the 14 GPa RMI experiment. Refer to Fig. 1 for the computational domain, rotated by  $90^\circ$  in this figure.

locally reaches 44% at the time of maximum spike velocity, the time we use for strength estimates. With the multiphase model, the mixed-phase treatment retains partial strength, and the calculated spike velocity still turns around at its peak as observed experimentally in Fig. 8. In fact, even later in time the model does not predict enough melt to capture the apparent jetting shown by the velocity in Fig. 8. The model may be underpredicting the melt, but the jetting also likely includes a contribution from damage evolution in the deforming regions, and damage is not modeled.

Higher shock pressures were considered for follow-up experiments to increase the sensitivity to the  $\gamma$ -phase strength, but the melting issue limits the increases that would still give useful strength data. The more straightforward approach to increase the sensitivity in the  $\gamma$  phase would be to use tamped RMI.

The 6 GPa RMI experiment also potentially has some melting. The simulation for  $\chi_\beta = 0.70$  and  $\eta_0 k = 1.0$  shows about 15% liquid mass fraction at the spike tip at the time of maximum spike velocity. The liquid fraction develops only in the last 10 ns or so before the maximum. Thus, the prediction of some liquid fraction is sensitive to the details. For example, increased strength leads to increased plastic work and higher liquid fraction.

The smaller  $\eta_0 k$  in all the RMI experiments do not have enough plastic deformation to reach the melt temperature. In all the RMI experiments, the simulations agree with the data equally well for all  $\eta_0 k$ , supporting the contention that partial melting is treated appropriately and is not affecting the estimation of  $\gamma$ -phase strength.

Note that running such simulations for the 6 GPa experiment without the multiphase model is problematic even though it does not reach the  $\gamma$  phase. When we simulated that experiment with a conventional modeling treatment, material at the spike tip reached the melt line, melted, and lost all strength, resulting in a jet, because, in such a model, a material

point must be either all solid or all melted. Clearly, from the velocity in Figure 6, there was no jet. With the multiphase model, the same material points only partially melted, retaining some fraction of solid material, and the mixed-phase strength was sufficient to suppress jetting and better captured the experiment.

### K. Interdependence and recalibration

The strength factor calibrations in this work came from simulations using a particular set of material models and parameters for the shear moduli, Taylor–Quinney coefficient, phase change kinetics, and the EOS, which itself includes phase boundaries, specific heat, thermal expansion, and more. Changing any one of those models might require one to recalibrate the strength factors. However, the sensitivity to such changes depends on what changes and by how much. The ramp-loading platform is so sensitive to EOS that it is commonly used for EOS studies, so, in general, a new EOS would require a recalibration of strength on the ramp-release data. (In the work here, the simulations of the loading portion of the velocities in Fig. 16 capture the data so well that the EOS should probably not need further adjustment in this regime.) RMI is less sensitive in general to the EOS since the Hugoniot state is usually modeled quite well. As another example, if our material model were revised to allow a variable (i.e., not 1.0) Taylor–Quinney coefficient, the temperature would change and likely affect the strength calibration. Because the temperature rise is greater for shock loading, RMI would be affected more. A back-of-the-envelope estimate for these experiments indicates the effect is small and would only move the calibration to slightly lower values of  $\chi_\gamma$ .

To check the need to recalibrate strength when any of the other material models are changed, one should resimulate the RMI and ramp-release experiments with the model changes and the existing strength calibrations to see if the simulated output used for calibration, the velocity, changes significantly.

Note that a change in a strength factor or other recalibrated parameter does not necessarily mean the strength itself has changed. The hydrodynamics of both the RMI and ramp-release experiments are governed by impulsive forces, inertia (i.e., density), and shear resistance (i.e., strength). Since a significant change to the density (from the EOS) in these modest regimes of pressure is unlikely, the strength magnitude required to match the measured velocities is essentially fixed. A good example of parameter changes without strength change would be the shear modulus. The shear modulus is used to scale the strength model, but on its own has a modest direct influence on the instability arrest in an RMI experiment, which is dominated by plastic deformation. If one doubles the shear modulus in the model, the strength factor would have to be approximately halved to match the measured velocity. The calibrated factor would have changed, but not the strength magnitude fed into the simulation.

## V. CONCLUSIONS

This work reports two independent experimental estimations of the dynamic strength of the body-centered tetragonal (bct)  $\gamma$  phase of tin, which occurs at pressures above about 9 GPa and transforms promptly back to the ambient  $\beta$

phase upon pressure release. One measurement used free-surface Richtmyer–Meshkov Instabilities (RMIs) achieved with gas gun impact. Another set of measurements used ramp-release loading in a pulsed-power facility. For both experiments, strength estimation came from comparison to simulations using CMMP, a comprehensive multiphase modeling framework. With the model comparison, the strength is characterized in terms of  $\chi_\gamma$ , a scale factor giving the strength relative to the strength of the ambient  $\beta$  phase. The RMI analysis gave  $\chi_\gamma = 0.0 + 0.24 - 0.0$  and the ramp-release gave  $\chi_\gamma = 0.13 \pm 0.1$ , very comparable results that are approximately within the uncertainty of no strength.

The existing literature on other materials, by contrast, almost universally reports higher strength in transient high-pressure phases compared with ambient phases. Recent Molecular Dynamics simulations on tin in the literature showed almost zero deviatoric strength during a deformation-induced bct  $\rightarrow$  bct transformation right after first entering  $\gamma$ , in which one of the  $a$  axes flips to the  $c$  axis. The occurrence of reorientation, as well as possible twinning, currently provides the most plausible explanation for the low observed strength in the  $\gamma$  phase.

To isolate  $\gamma$ -phase strength in the high-shock RMI experiment, two lower-pressure experiments below the phase change were first used to assess  $\beta$ -phase strength at the extreme strain rates of RMI. Fitting the  $\beta$ -phase strength required a 30%–40% reduction of a PTW strength model. The PTW model had been calibrated to stress-strain curves at rates up to  $4000 \text{ s}^{-1}$ , whereas the RMI experiments exercised rates up to almost  $10^7 \text{ s}^{-1}$ . Hence, the strength reduction accounted for an inaccurate extrapolation to higher rates. For the 4 GPa experiment, the strength was estimated at  $500 \pm 60 \text{ MPa}$  at  $6.6 \times 10^6 \text{ s}^{-1}$  and for the 6 GPa experiment  $660 \pm 60 \text{ MPa}$  at  $8.5 \times 10^6 \text{ s}^{-1}$ . The analysis also indicated that these two estimates of average strength were accurate enough to be used as simple calibration points for fitting a strength model, eliminating the need for tedious simulations each time one wanted to include RMI data in the calibration.

Simulations indicated localized partial melting in a couple perturbation regions of the RMI experiments caused by plastic work heating near the tip of the spike, making those three-phase experiments. The CMMP model gave a peak of 44% liquid mass fraction at the time of maximum spike velocity in the 14 GPa experiment with the largest  $\eta_0 k$ , 0.7, and 15% liquid mass fraction for the 6 GPa experiment with  $\eta_0 k = 1.0$ . In such mixed-phase regions the CMMP model still returns partial strength, and the spike velocities agree well with the data. Simpler models in which material fully melts upon reaching the melt temperature would predict instability and jetting, which was not observed.

Tamped RMI experiments would provide a promising next step by holding in the  $\gamma$ -phase longer to increase sensitivity and also possibly exercising increased plastic strains to look for the return of strength after exhausting the bct  $\rightarrow$  bct reorientation.

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#### DATA AVAILABILITY

The data that support the findings of this article are not publicly available because of legal restrictions preventing unrestricted public distribution. The data are available from the authors upon reasonable request.

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