Modeling and analysis of high-explosive driven perturbed plate experiments at Los Alamos

James H Cooley[1], Russel T Olson[2] and David Oro[2]

[1]Theoretical Design Division, Los Alamos National Laboratory, Los Alamos, NM, USA
[2]Physics Division, Los Alamos National Laboratory, Los Alamos, NM, USA

E-mail: `jhcooley@lanl.gov`

Abstract. We have carried out several experiments on the Los Alamos proton radiography (pRad) facility to explore the growth of perturbations subjected to shockless acceleration. These experiments have involved both Tantalum and depleted Uranium plates with various initial amplitudes. The experimental platform is based on the one first developed by Barnes et al. [1] and further advanced by Raevsky [2]. This paper presents both the data for these experiments and an initial attempt to model the experiments using the simulation code FLAG [3].

1. Introduction

There has long been significant interest in understanding the plastic behavior of solids under dynamic loading conditions. Various theoretical and computational models have been developed to explain flow resistance to high strain and strain-rate deformations. The model proposed by Steinberg and Guinan (SG) [9] assumes a constant strain-rate and is calibrated in the high-rate regime. The Preston-Tonks-Wallace (PTW) [6] model includes a strain-rate dependence that is calibrated at low to intermediate rates with experimental data. The model is calibrated to high strain-rates with a theoretical model while the intermediate regime is interpolated between the two extremes. Calibration of plastic flow models at intermediate strain and strain-rate have used various notched bar techniques. Validation has depended on the comparison of simulations to data obtained using cylindrical impact experiments [5].

Classic fluid instabilities have been used to excite large deformation flow of perturbed interfaces. The initial classic experiments that examined these flow conditions were conducted at Los Alamos by Barnes [1]. This data has been used by several efforts to understand the theoretical behavior of materials with strength [7, 8]. Several recent experiments have been performed under shock accelerated conditions where a perturbed interface is subjected to Richtmyer-Meshkov instability [10]. The experiments discussed in this paper are part of a series that involve the shockless acceleration of solids using an expanding high-explosive detonation gas [11]. This acceleration results in the metal plate under going classical Rayleigh-Taylor instability.

2. Experimental discussion and results

The experimental set-up for these experiments is shown in figure 1. The target plate is between 1.5 mm for depleted Uranium (DU) to 1.6 mm in Tantalum (Ta). This set-up is based on the improvements to the experiment design developed by V. A. Raevsky [2]. In this configuration, a steel plate is accelerated across a gap by a high-explosive plane wave lens. This steel plate impacts a booster charge of PBX9501 and ignites the charge. The booster detonates and the product gas is expanded across a vacuum gap to provide a shockless acceleration of the perturbed target plate. The accelerated steel plate continues to compress the detonation products and provides peak pressure at the target surface of around 400 Kbar.

We measure the actual drive on the back surface of the plate using PDV at several radial locations. In figure 1 we have included an insert that shows the measured drive for a couple of Ta and DU targets. We use these PDV measures to help calibrate the simulation drive to ensure we match the acceleration history of the experiment.

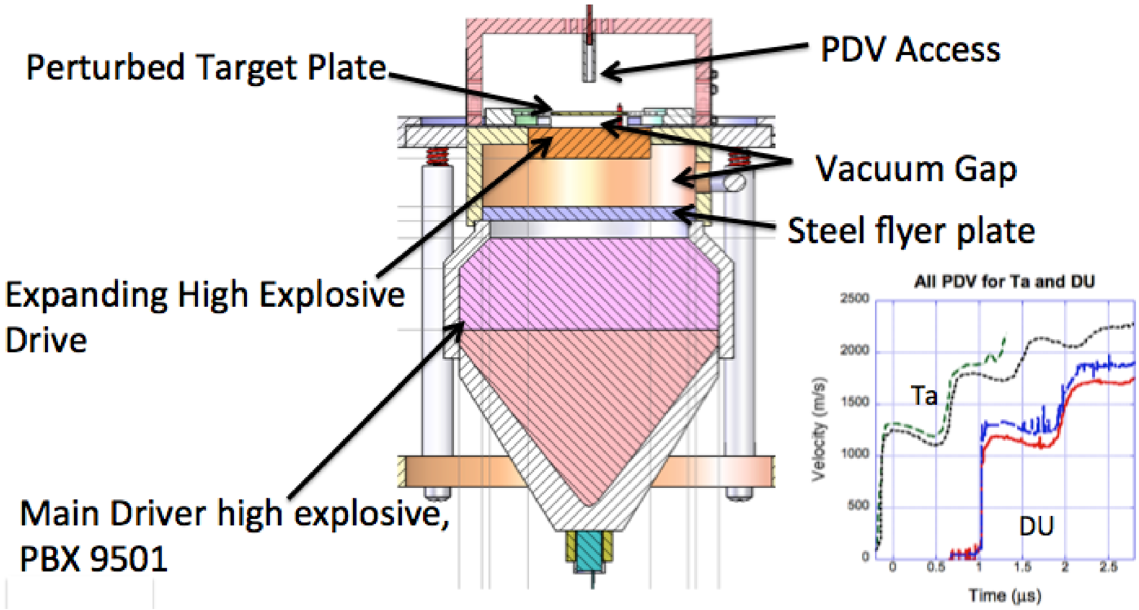

Figure 1. Experimental set-up for perturbed plate experiments. Insert shows the measured PDV drive at the target center for each of the two Tantalum and depleted Uranium experiments. Notice that the peak velocities vary slightly; however, the acceleration structure appears repeatable.

These experiments were conducted on the Los Alamos Proton Radiography (pRad) facility. This facility allows us to take several images of the evolution on the same experiment. We collected 19 images for these experiments that were separated by 0.4 μs presented in figure 2. The result shown in figure 5 is an image from an intermediate time and has been processed using Abel inversion to remove the symmetric overburden. However, for these high-Z targets we have found that there is a loss of resolution in the central region due to inadequate proton flux through the target. This loss of resolution makes interpreting the results in the intermediate times, image 10-13, for the experiment problematic. (This experimental issue does not impact lower-Z targets such as Copper [11].)

We extract the distance from the tip of the finger to the back of the bubble. It is the bottom of the bubble that poses the extraction problem at certain times. You can see from the images that the instability has resulted in significant plastic deformation by the middle of the experiment. In fact, the perturbations have stretched the target to a width that is significantly thicker then the original plate. We have done several experiments with Ta using different material processing, small and large grain. These experiments show no measurable difference between the different processing.

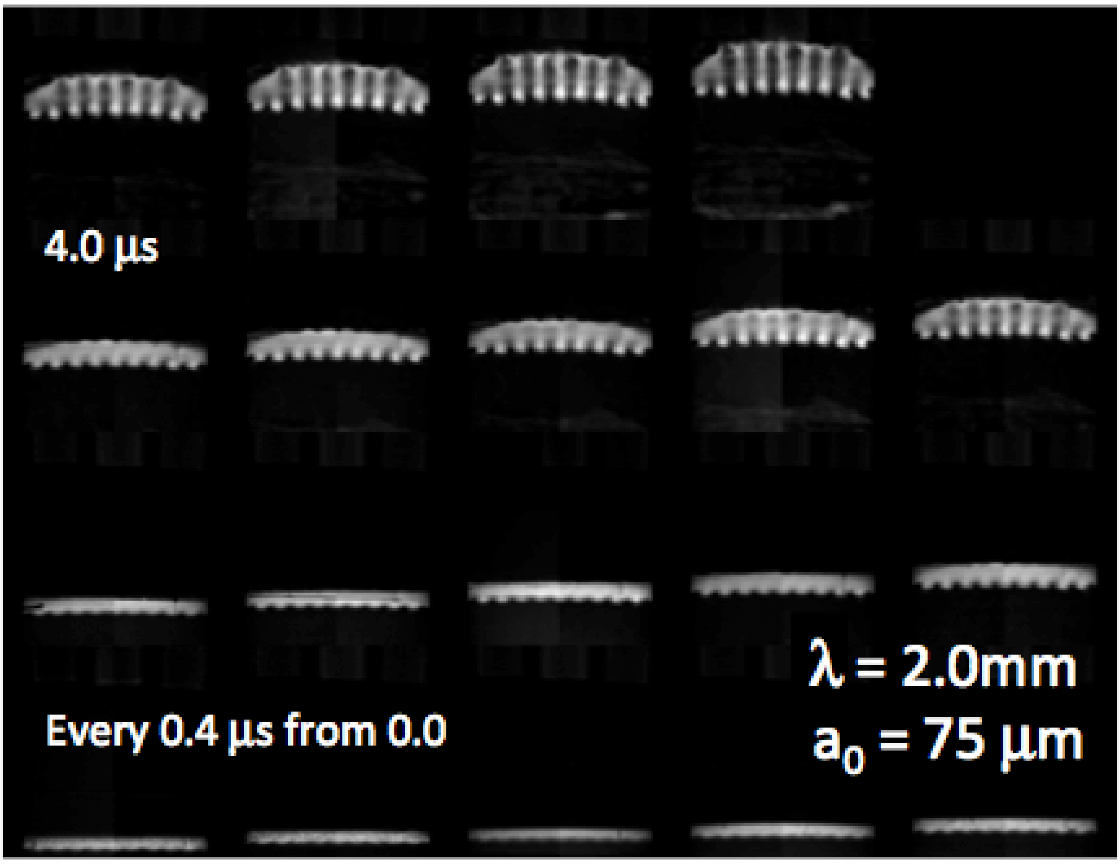

Figure 2. Experimental data for the depleted Uranium experiment pRad 352. The images are the transmission inverse after removing the symmetric overburden, effectively density, separated by 0.4 μs. The perturbation wavelength is $\lambda = 2.0\ mm$ with an initial amplitude, $a_0 = 75\ \mu m$ or 150 μm peak to trough. In this image one can see an initial growth phase for the perturbation. In the intermediate times you observe an obfuscation of the top of the bubble. At late times one observes a large and rapid instability growth.

3. Theoretical and simulation analysis

We simulated these experiments with the Lagrange-ALE code FLAG [3] using several published constitutive strength models. We performed a resolution study to ensure we were converged to the quantity of interest for these experiments, namely the peak-to-trough length. We performed the simulations by constructing a model with several perturbation wavelengths across the target. The left and right boundaries were constrained to only move in the direction of the HE drive. The initial velocity of the steel flyer plate was slightly adjusted so that the simulated PDV velocity profile at the rear of the target plate matched the experimental data. Figure 3a demonstrates the close match between the data and the simulation. The pressure drive across the simulation was uniform as shown by figure 3b where with the exception of the initial peak excursion, both the finger and bubble interfaces see identical pressure profiles in time.

In figure 4, we show the measured peak-to-trough length as a function of time along with the results of extracting this length from several simulations. The simulations track the measured amplitude well for the early time. PTW does appear to match the data more closely then SG as we approach 3 μs. However, at late time you see the measured amplitude acquire a more rapid growth rate while the simulations appear to saturate. We are not yet sure how to interpret this experimental result.

The simulation shows the maximum temperature of the DU remaining well below possible melt conditions so it is unlikely that the the material is melting. We have also compared the simulated material phase space condition with a multiphase Uranium phase diagram to evaluate a possible solid phase transition but this hypothesis also appears unlikely based on the distance of the phase boundary to the simulated region. One plausible hypothesis is that the DU may fail in some manner after a significant amount of plastic strain. This failure mode is not captured with our current models. This failure mechanism would need to work under a compressive load as even at late time the HE is sustaining a significant pressure on the target. However, there are other experiments with extruding DU that are consistent with this finding and which have not yet been explained with a complete model. In particular, when DU is subjected to large deformation flow in extrusion experiments the DU appears to become rubble rather then continuing to have plastic behavior to large deformations [4].

Even though we do not currently have an explanation for the failure, we attempted to model this type of behavior. We performed a simulation using the PTW model for the initial time of the simulation. Then at a specified time in the calculation we removed the PTW model and replaced it with a model that did not have any constitutive flow resistance. This simulation result is shown in red in figure 4. Our attempts to capture the large growth rate at late times by turning off flow resistance have not yet yielded satisfactory results and further analysis and comparison work is necessary.

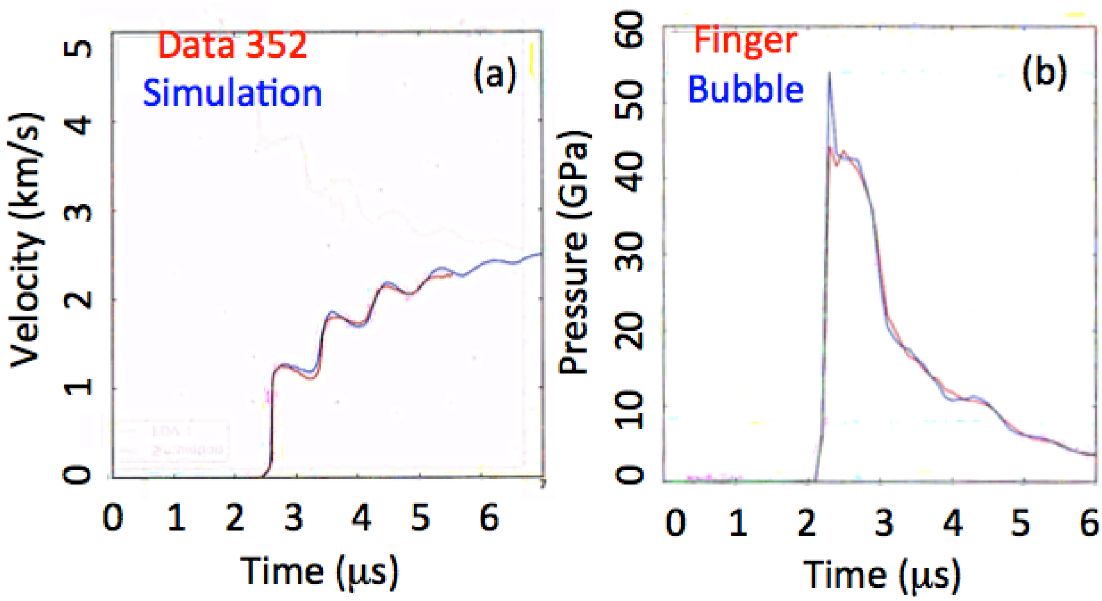

Figure 3. Figure (a) shows a comparison of the simulated drive, in blue, with the PDV data, in red, from the DU experiment pRad 352. In the simulation we adjusted the initial steel plate velocity slightly to match the back-surface PDV signal. Figure (b) shows the time history of the pressure just at the HE to target interface at a location in the peak of the finger, red, and the bottom of the bubble, blue. There is a difference at the initial peak pressure but then the target appears to have a uniform pressure drive across the simulation.

One interesting observation is that the DU growth data appears to have a behavior that is beginning to saturate at around 3.6 μs just prior to the region of very rapid growth. The simulation results appear to support a saturation behavior and they begin to oscillate at around 600 μm in amplitude. Clearly the instability growth is not arrested at late times in the data.

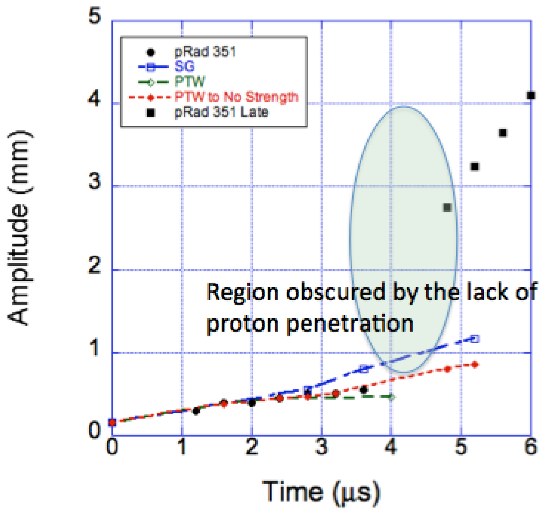

Figure 4. Experimental amplitudes extracted from DU pRad 352 experiment along with a couple of different simulation models. Notice that the late time growth in the data is not captured by any of the simulated models although PTW captures the early behavior well.

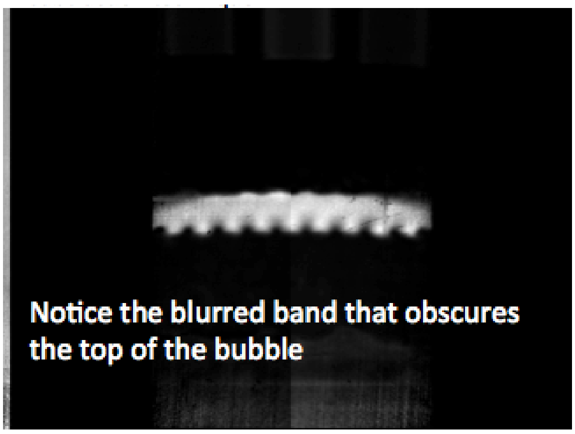

Figure 5. One of the DU images processed to eliminate axis symmetric overburden. Notice the blurred region in the center of the target which obscures the bottom of the bubble. This image corresponds to a time represented by the green region in figure 4

However, it is possible that the DU flow resistance is large enough at lower plastic strains that it should arrest and that there is some other catastrophic failure that leads to the continued, and increased, instability growth as discussed above.

To understand whether we might expect saturation or continued growth in the presence of a uniform strength model we have applied the criteria for unstable growth developed by Robinson and Swegle [8]. We have taken the yield strength from Steinburg [9] and used it to calculate $\delta h \approx 4Yh/\sqrt{3}P_m$ from [8], where Y is the maximum yield strength, h is the thickness of the plate and P_m is the maximum pressure of the drive. For the conditions of the DU experiment we have $P_m = 400\ kbar$, $Y = 16.8\ kbar$, and $h = 1.5\ mm$ leading to $\delta h = 145\ \mu m$. This value is larger than the initial amplitude of 75 μm so we would expect the instability to saturate. Both the simulation and experiment, at early times, appear to saturate as expected; however, the experiment then undergoes rapid growth which is not yet understood theoretically.

We have conducted similar experiments with Ta using different grain size material. These experiments have demonstrated no difference in strength behavior under these loading conditions for the different grain size material. The results of some of these experiments have been previously published by Barton et al. [12]. Further examination of the data indicates that there may be a systematic bias in the results that would need more interpretation to fully address and is not included in the current effort. However, it is clear that at around 5 μs the amplitude is around 1.5 mm based on comparisons of the amplitude to the wavelength. Further experiments with Ta would likely be warranted if a detailed quantitative comparison is to be pursued.

4. Conclusions

We have presented details of Rayleigh-Taylor instability experiments performed on the Los Alamos National Laboratory pRad facility on DU and Ta. These high-Z materials had a reduced resolution during the intermediate stage for the evolution due to a lack of proton flux through

Journal of Physics: Conference Series **500** (2014) 152003 doi:10.1088/1742-6596/500/15/152003

the middle of the target. We presented the results of simulations compared to the DU data. These simulations show reasonable comparison during the early stages of evolution; however, the late stage large growth has not yet been reconciled. The distinct behavior in DU which appears to have two distinct growth rates, one for early time and one for late time, is qualitatively consistent with DU extrusion experiments performed at LANL. We examined the Ta data and determined that there is some uncertainty in the analysis which makes quantitative comparison problematic. If further work were to be performed on Ta using these experiments then additional data would be required to quantitatively compare to hydro-code calculations.

References

[1] Barnes J F, Blewett P J, McQueen R G, Meyer K A and Venable D 1974 Taylor instability in solids *J. Appl. Phys.* **45** 727
[2] Raevsky V A 2009 *Influence of dynamic material properties on perturbation growth in solids*, Technical Report, All-Russian Research Institute of Experimental Physics, VNIIEF
[3] Caramana E J, Burton D E, Shashkov M J and Whalen P P 1998 The construction of compatible hydrodynamics algorithms utilizing con- servation of total energy *J. Comput. Phys.* **146** 227262
[4] Chen S R 2013 Private communications with LANL MST
[5] Maudlin P J, Bingert J F and Gray III, G T 2003 Low-symmetry plastic deformation in BCC tantalum: experimental observations, modeling and simulations *International Journal of Plasticity* **19** 483-551
[6] Preston D L, Tonks D L and Wallace D C 2003 Model of plastic deformations for extreme loading conditions *J. Appl. Phys.* **93** 211-220
[7] Drucker D C 1980 A further look at Raleigh-Taylor and Other Surface Instabilities in Solids *Ingenieur-Archiv* **49** 361-367
[8] Robinson A C and Swegle J W 1989 Acceleration instability in elastic-plastic solids II. Analytic techniques *J. Appl. Phys.* **66** 2859
[9] Steinberg D J, Cochran S G and Guinan M W 1980 A constitutive model for metals applicable at high-strain rate *J. Appl. Phys.* **51** 1498
[10] Prime M, Vaughan D, Preston D, Oro D, and Buttler W 2013 Using growth and arrest of Richtmyer-Meshkov instabilities and lagrangian simulations to study high-rate material strength *Submitted to these conference proceedings*
[11] Olson R T and Oro D 2013 The effect of microstructure on Rayleigh-Taylor instability growth in solids *Submitted to these conference proceedings*
[12] Barton N R, Bermier J V, Becker R, Arsenlis A, Cavallo R et al. 2011 A multiscale strength model for extreme loading conditions *J. Appl. Phys.* **109** 073501