Beryllium Strength under Extreme Dynamic Loading Conditions

Marc Henry de Frahan[1] J. L. Belof[2] R. M. Cavallo[2] O. Ignatova[3] E. Johnsen[1] B. A. Remington[2] V. Raevsky[3]

[1]University of Michigan, [2]Lawrence Livermore National Laboratory, [3]RFNC-VNIIEF

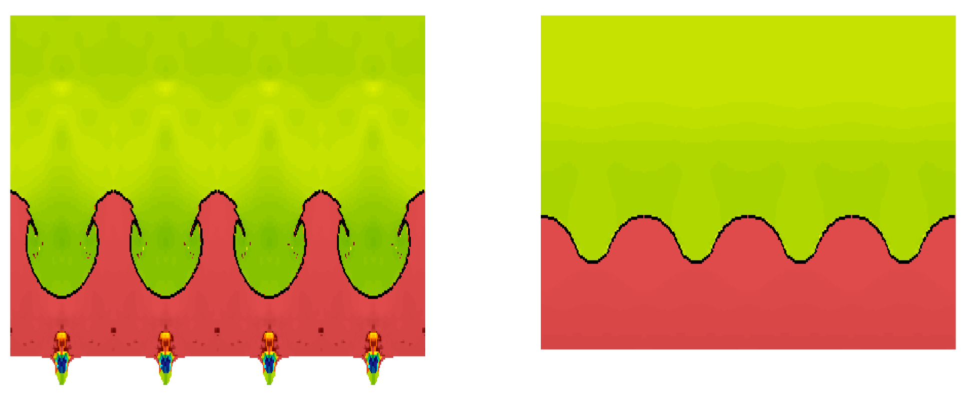
Abstract

Beryllium strength has been investigated under dynamic loading conditions using platforms that span a limited range of pressure and strain-rate space. Multiple Be strength models that are ostensibly calibrated to these experiments persist, and yet they predict different outcomes for results beyond the limited phase space where data exist. We discuss experiments using high explosives (HE) to accelerate a solid rippled Be target quasi-isentropically. The interface between the low-density gaseous HE and the perturbed face of the solid target is Rayleigh-Taylor (RT) unstable. The amplitude of the ripples will grow with time, and the Be strength will mitigate the ripple growth. By measuring and modeling the amplitude growth, we can discriminate among various strength models for Be. Our RT designs extend the pressures up to 50 GPa and the strain-rates to $10^6 s^{-1}$*. As a part of the design process, we analyze existing plate impactor and Taylor anvil experiments using available models. We present the results of this analysis as well as the designs and preliminary experimental results from the RT experiments.*

Background and Motivation

Material strength mitigates RT growth (Fig. 1).

- Hydrodynamic instabilities can quench ignition by mixing the cold fuel with the hot ablator.
- Because of its strength, Be can be an alternative to current CH ablator in the NIF capsules.
- Be can be used as a heat shield in other material experiments (Fig. 9).



(a) Without material strength. (b) With material strength.

Fig. 1: Pseudocolor of density illustrating RT growth in an Ares simulation.

There are many competing material strength models.

- Existing strength models are phenomenological and established with physics-based ansatz.
- They are calibrated at low pressure and low strain-rate ranges.
- Outside this range the models diverge significantly (Fig. 2).

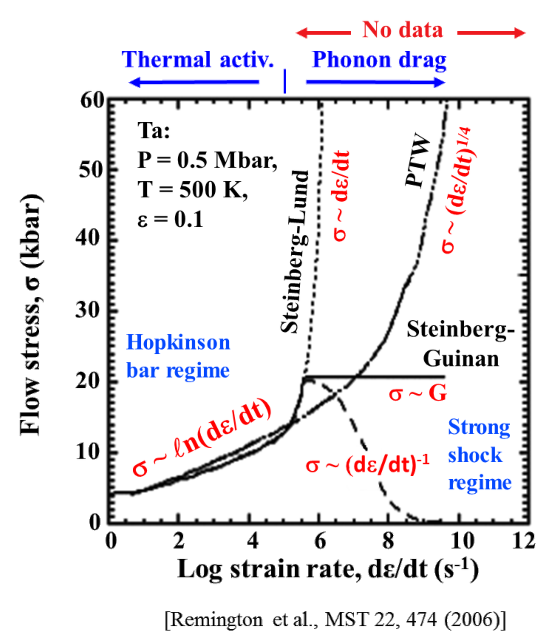


Fig. 2: Existing strength models diverge in the high strain-rate regime.

Objectives

1. **Try to discriminate among various models using existing Be data.**
2. **Design high pressure RT experiments to explore new regimes.**
3. **Evaluate the different Be strength models using these new data.**

Analysis of existing data

Methods

We compare 1D and 2D experiments of Be under various loading conditions using

- existing data compiled by collaborators at the Russian Federal Nuclear Center (VNIIEF)
- Ares, an ALE hydrodynamics code developed at LLNL.

Plate-impactor experiments (1D)

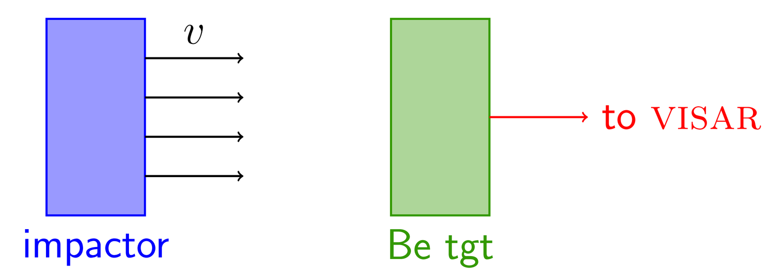
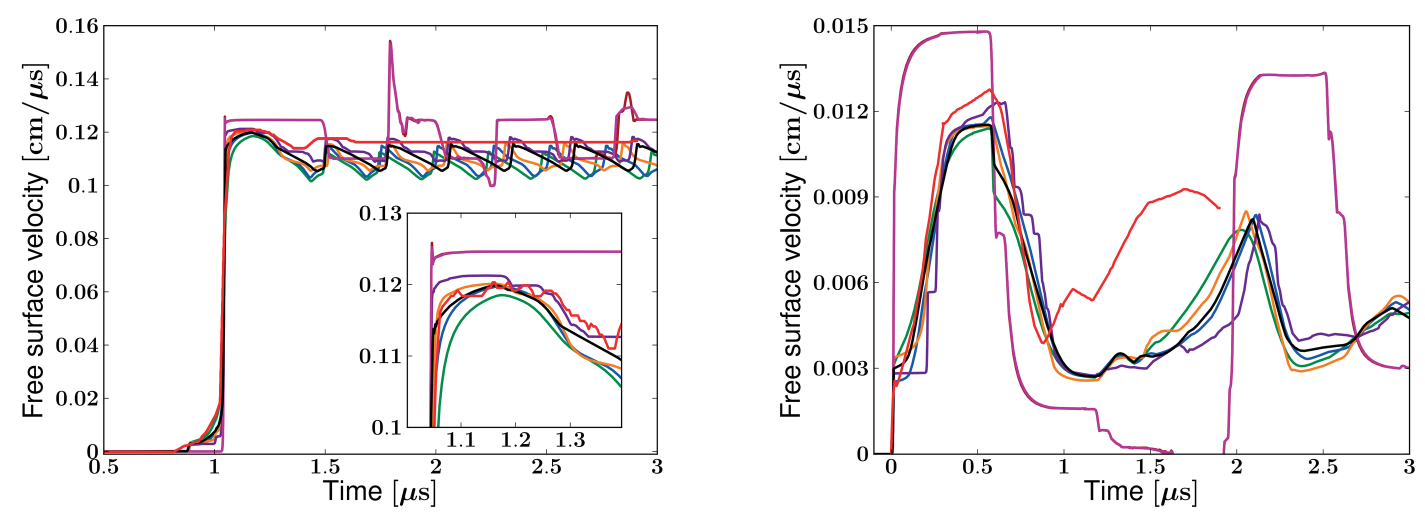


Fig. 3: Impact of a Be target by a variety of impactor materials (Ta, Sapphire, Al, Steel, Be, Cu) spanning a wide range of impact velocities (0.002cm/μs to 0.2cm/μs). The free surface velocity is measured by VISAR.



(a) 0.2cm Be impactor on 0.4cm Be target at 0.12cm/μs. (b) 0.2cm Al impactor on 0.5cm Be target at 0.014cm/μs.

Fig. 4: Exp. data, PTWP, PTWB, PTWC, SG, JC, ZA, and SL (see summary).

Taylor anvil experiments (2D)

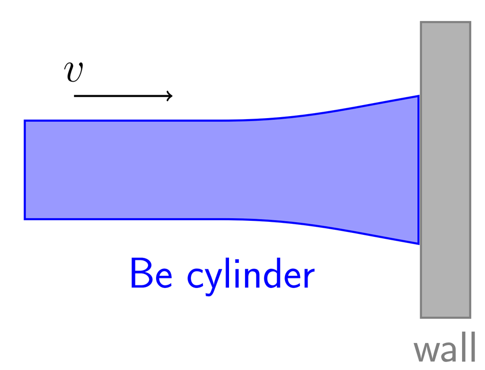


Fig. 5: Uniaxial compression of Be cylinders with impact velocities ranging from 0.015cm/μs to 0.027cm/μs.

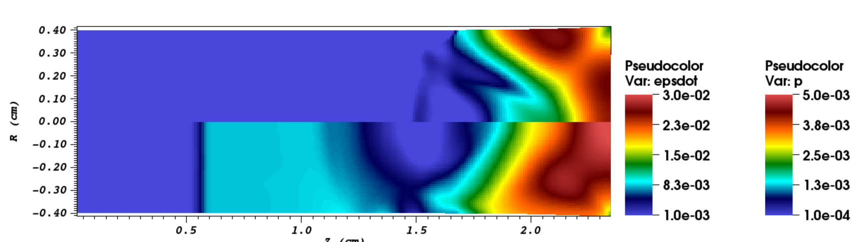


Fig. 6: Strain-rate (μs^{-1}, top) and pressure (Mbar).

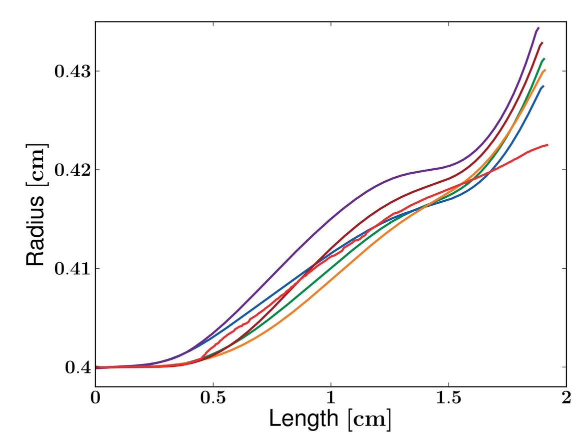


Fig. 7: Recovered cylinder profile: exp. data, PTWC, PTWB, PTWP, SG, and SL.

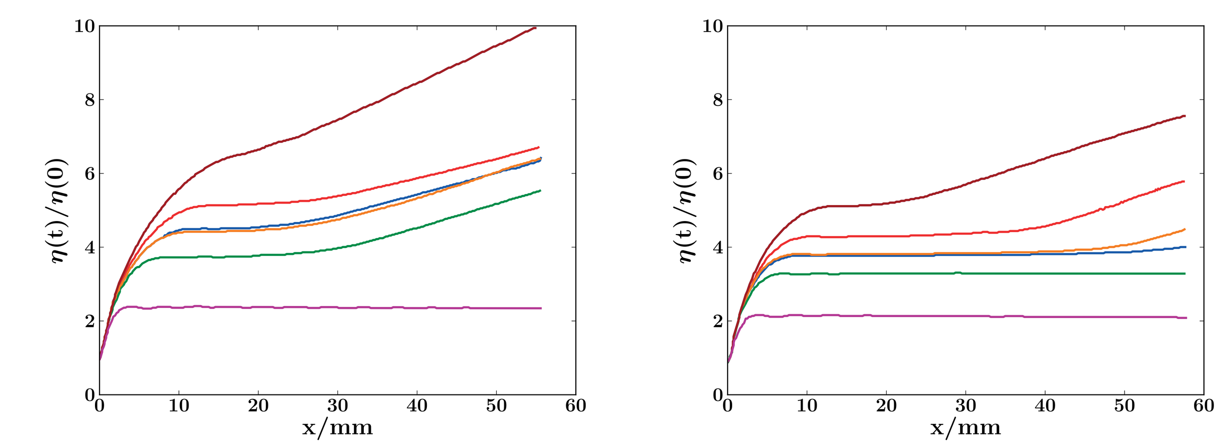
Conclusions

- The strength models capture the material behavior.
- We are unable to discriminate among the different models using existing data (except for JC and ZA).
- Models diverge significantly in high pressure and high strain-rate regimes.

Future RT experiments

Collaboration with RFNC-VNIIEF for HE driven rippled Be tgts

- Characterize RT growth;
- Recover samples to determine deformation physics (dislocation, twinning,...).
- Predictions show that we will be able to discriminate among some of the models (Fig. 8).



(a) $\lambda = 4\text{mm}$, $A_0 = 250\mu\text{m}$, $\Delta x = 2\text{mm}$. (b) $\lambda = 4\text{mm}$, $A_0 = 200\mu\text{m}$, $\Delta x = 1.75\text{mm}$.

Fig. 8: Predicted RT growth factors as a function of displacement relative to starting position of the Be target: PTW nominal, PTWP, PTWB, PTWC, SG, SL, and MTS.

Future laser RT exp. to explore the high strain-rate regime

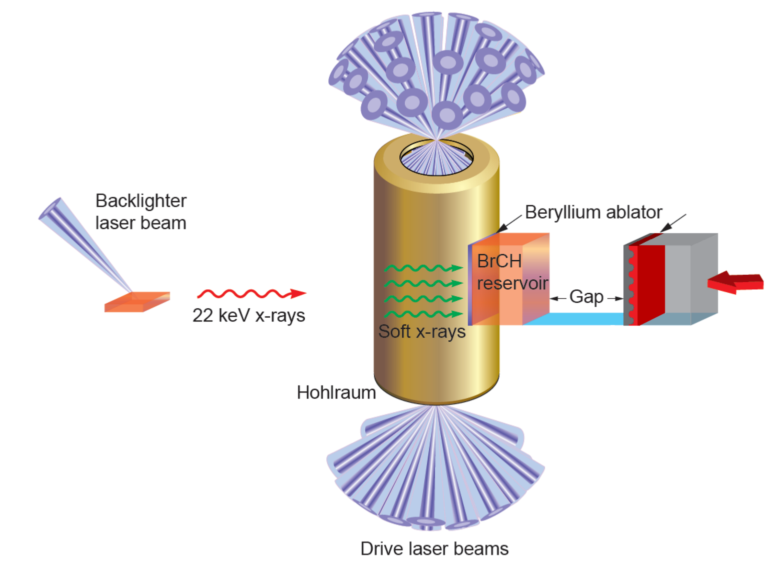


Fig. 9: Be is used as a heat shield in this laser RT experiment.

Summary of Strength Models

Johnson-Cook[1]: work hardening, thermal softening, strain-rate hardening
Steinberg-Guinan[2]: JC with different ansatz + pressure hardening
Steinberg-Lund[3]: SG + strain-rate dependence
Zerilli-Armstrong[4]: simplified dislocation mechanics
Preston-Tonks-Wallace[5]: combines thermal activation and phonon drag different fits (Preston, Blumenthal, and Chen)[6]

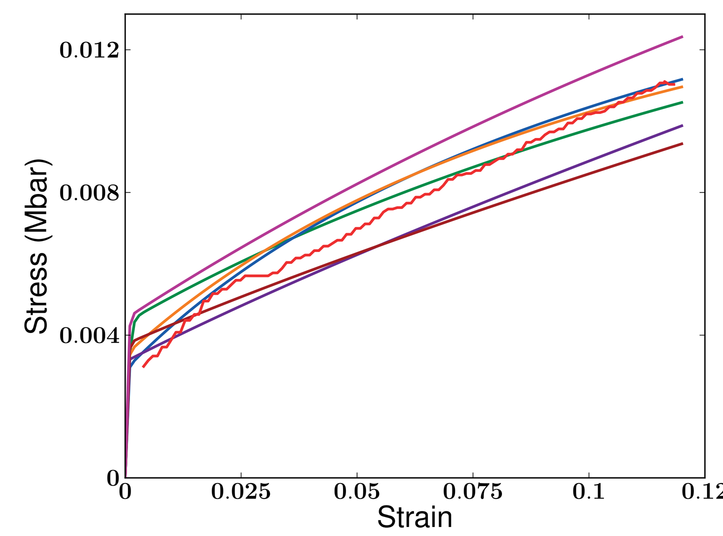


Fig. 10: Be at 0.0035 μs^{-1} strain-rate: exp., PTWP, PTWB, PTWC, SG, SL, and MTS (from MIDAS database).

Bibliography

[1] G. R. Johnson and W. H. Cook. In *Proc. 7th Intern. Symp. Ballistics*, pp. 541–547 (1983).
[2] D. J. Steinberg, S. G. Cochran, and M. W. Guinan. J. of Appl. Phys. **51**, 3 (1980).
[3] D. J. Steinberg and C. M. Lund. J. of Appl. Phys. **65**, 4 (1989).
[4] F. J. Zerilli and R. W. Armstrong. J. of Appl. Phys. **61**, 5 (1987).
[5] D. L. Preston, D. L. Tonks, and D. C. Wallace. J. of Appl. Phys. **93**, 1 (2003).
[6] S. Chen and G. T. Gray. Los Alamos Technical Report LA-CP-04-0920 (2004).

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.