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Estimation of Yield Strength under Shock and Ramp Loading up to 60 GPa from Numerical Simulations of Quasi-elastic Unloading Response

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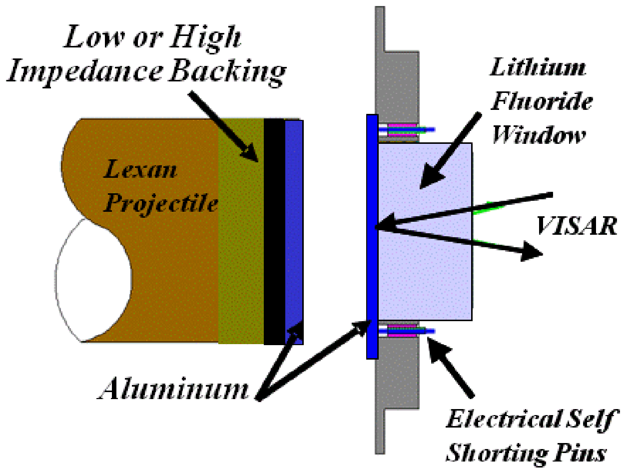
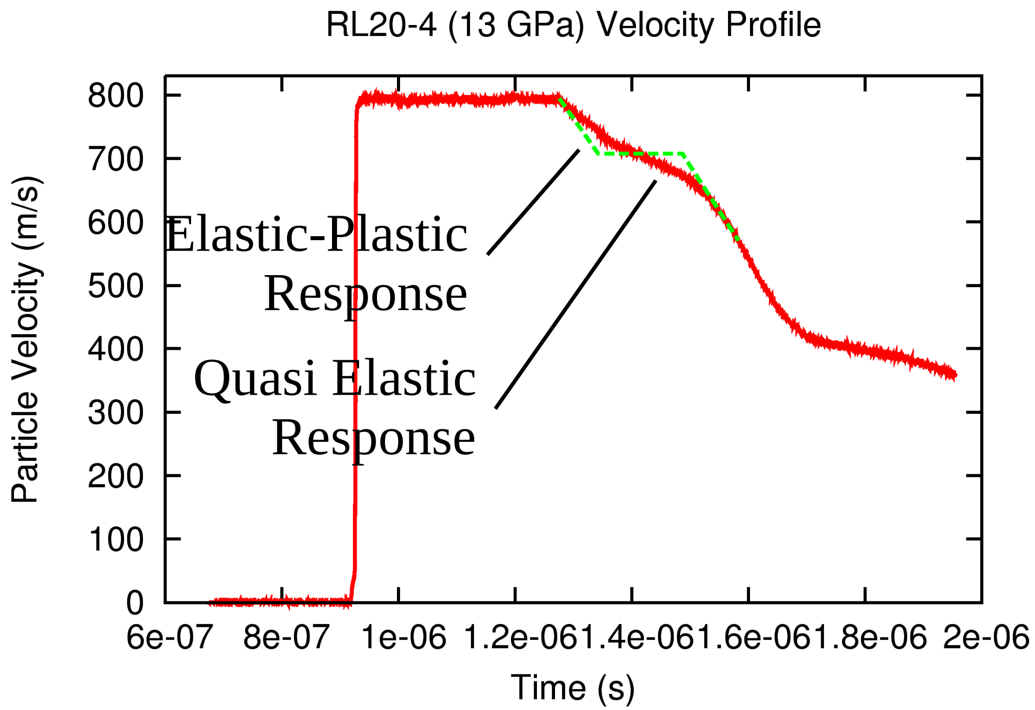
Quasi Elasticity

Quasi-elasticity: "anomalous elastic-like loading, which results from initial elastic material response followed by a mixed elastic-plastic deformation" - H. Huang and J. R. Asay





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Problem Statement

Analytic analysis is typically used to extract strength information from shock experiments. This is particularly difficult when one or more of the following are present:

1) Impedance mismatch (between flyer/target or target/window)
2) Ramp loading (complex wave interactions)
3) Wave attenuation

The purpose of this research was to determine the feasibility of determining material parameters under high pressures with current modeling and optimizing techniques and to compare results with analytically determined values.

Assumptions

- The elastic-plastic model ($\sigma = P + 4/3\ \tau$)
- There exists a Von Mises yield surface
- The simulated shocked state is located on the yield surface
- There is no rate dependence in the models
- The strain rates are greater than roughly $10^5\ sec^{-1}$
- In simulations, the temperature effects can be neglected

Programs and Models

- **Optimization Software: DAKOTA**
  - Optimization software with special focus on design analysis and optimization for engineering applications. DAKOTA was used for optimizing material parameters and for sensitivity analysis of the converged solution.
  - The newest version (5.0) is available under the GNU Lesser General Public License (LGPL) from dakota.sandia.gov
- **Simulation Software: LASLO**
  - A lightweight one-dimensional Lagrangian shock code that supports anisotropic symmetries and user-defined tabular time-dependent velocity and pressure boundary conditions for simulation of arbitrary ramp loading as well as shock loading.
- **Mie Gruneisen EOS Model**
- **Modified Steinberg-Guinan Strength Model**
  - ...

Modified Steinberg-Guinan Constitutive Model

For the initial shocked state the classical form is followed, neglecting temperature dependence, until the onset of release:

$$G = G_0 \left[1 + A \frac{P}{\eta^{1/3}} - B \left(T - 300 \right) \right]$$

$$Y = Y_0 \left[1 + \beta(\epsilon + \epsilon_i) \right]^n \left[1 + A \frac{P}{\eta^{1/3}} - B \left(T - 300 \right) \right]$$

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Modified Steinberg-Guinan Constitutive Model

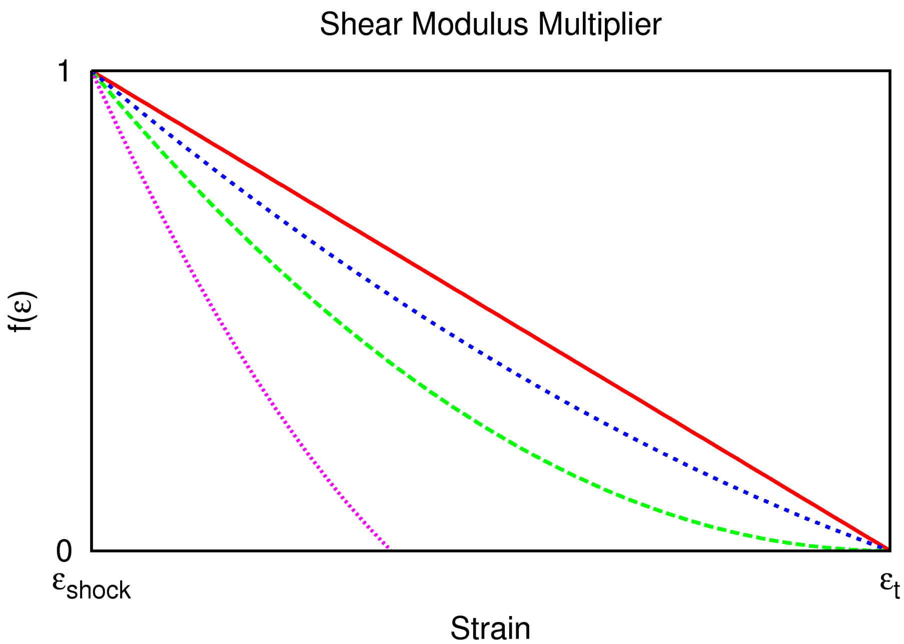
The QE response indicates that the shear modulus varies while the material transitions from elastic to plastic response. Let us define a function that controls how the shear modulus goes to zero. For simplicity, we will refer to this monotonic function as f(ϵ) and define it as follows:

$$\epsilon_t = \epsilon_{shock} + \frac{2Y_{shock}}{G_{shock}}$$

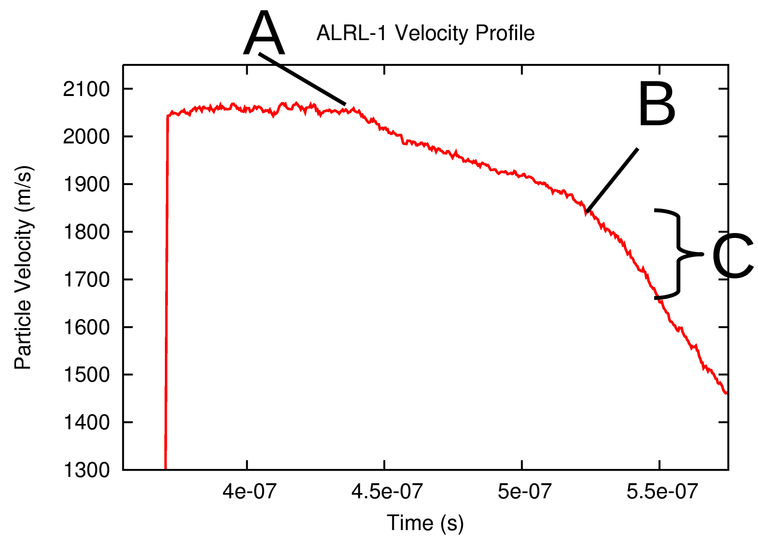
$$f(\epsilon_{shock}) = 1$$

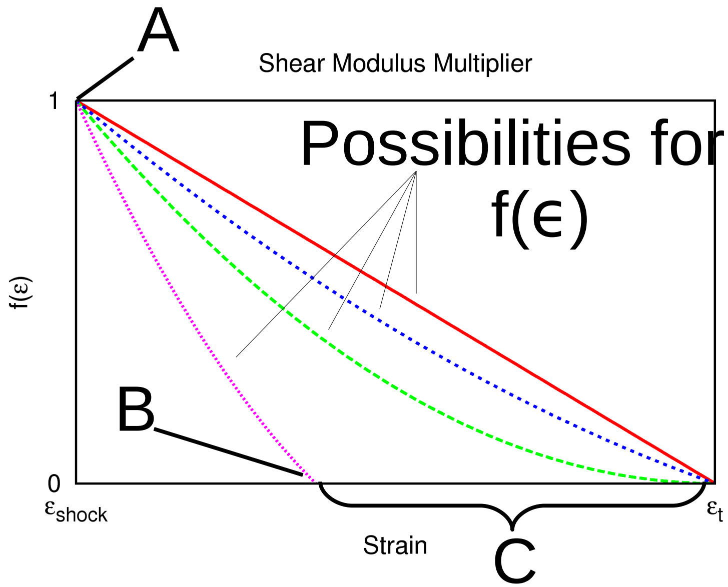
$$f(\epsilon_t) = 0$$

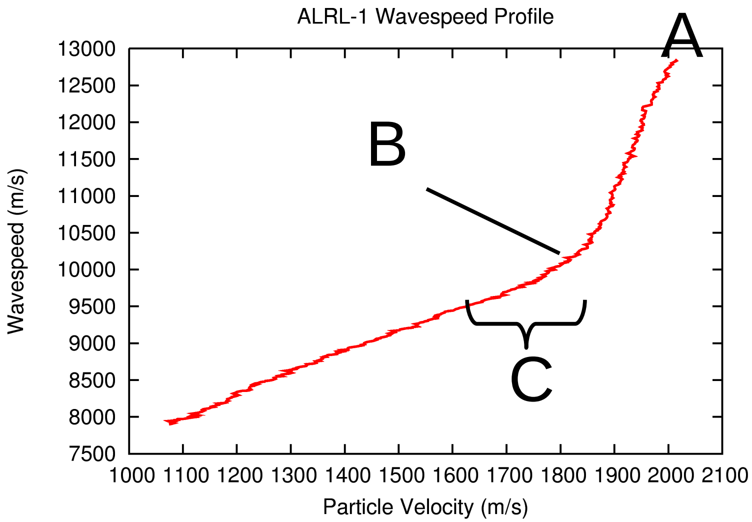
$$G_{eff} = G_{shock} f(\epsilon)$$



Quasi Elastic Relationships







Optimization Approach

• Run several simulations by hand to ensure that the setup, boundary and initial conditions, and EOS parameters are set so that bulk response is correctly modeled.

• Optimize the simulated output using the parameter Y_0 and the function f(ϵ) against the experimental data. The objective function for optimization was the standard deviation of the differences between the experimental and simulated profiles.

• Determine If the optimization process converged to a local or global minimum.

• Analyze the data. This includes finding the yield stress at peak stress and scaling it by a factor proportional to f(ϵ)...

Scaling the Yield Stress

It is suspected that the Steinberg-Guinan model has significant limitations for determining yield strength correctly. The 'exact' value of yield stress at high pressures deviates significantly from the theoretical value given by the Steinburg-Guinan model.

It is common practice to use the wavespeed-strain profile to analytically determine the 'exact' yield stress. Logically, it follows that if the measured particle velocity can be reproduced to high accuracy, the wavespeeds and strains must be accurate as well, entailing that simulation contains the information for yield stress.

The value for yield stress is found by integrating the shear modulus in strain space through unloading. For our simulations, this is the best representation of yield strength because it is independent of the model's function for computing yield stress!

Derivation of Technique

$$
\begin{aligned}
dY' &= \frac{3}{4}\rho\left(a_W^2 - a_B^2\right)d\epsilon \\
&= \frac{3}{4}\rho\left(a_W^2 - a_B^2\right)\frac{\left(a_L^2 - a_B^2\right)}{\left(a_L^2 - a_B^2\right)}d\epsilon \\
&= G\left(\epsilon\right)\frac{\left(a_W^2 - a_B^2\right)}{\left(a_L^2 - a_B^2\right)}d\epsilon \\
&= G\left(\epsilon\right)h\left(\epsilon\right)d\epsilon \\
Y' &= \int_0^{2Y/G_{shock}} G\left(\epsilon\right)h\left(\epsilon\right)d\epsilon = \int_0^{2Y/G_{shock}} G_{shock}f\left(\epsilon\right)d\epsilon \\
&\Rightarrow 2Y_{max}\int_0^1 f\left(\xi\right)d\xi
\end{aligned}
$$

If Y and G are assumed constant in the QE region

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Definition of Y'

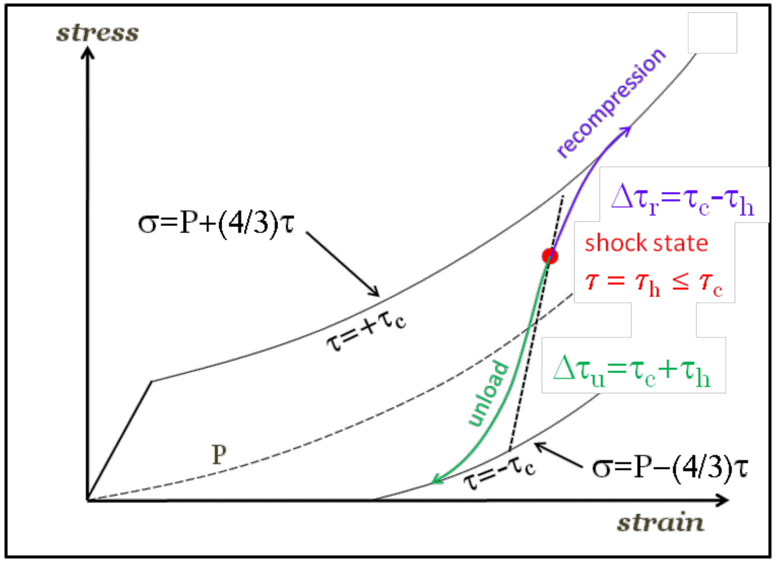
Although the assumption was made that the simulated shock state lies on the yield surface, the definition and calculation of Y' does not. Typically,

$$Y' = 2\tau_C$$

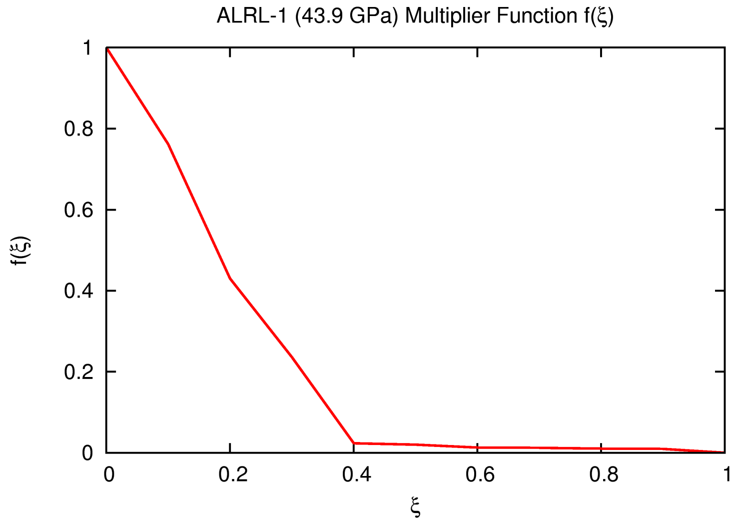
but reshock experiments suggest that the shocked state does not lie on the yield surface. So,

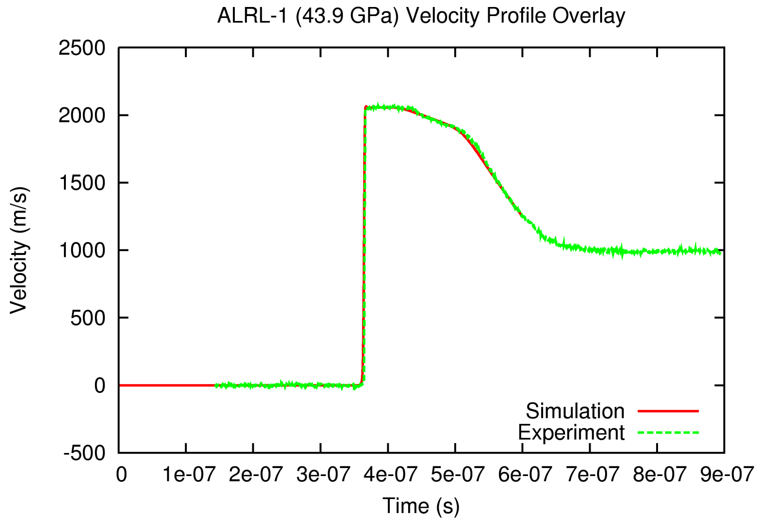
$$Y' = \tau_C + \tau_H \leq 2\tau_C$$

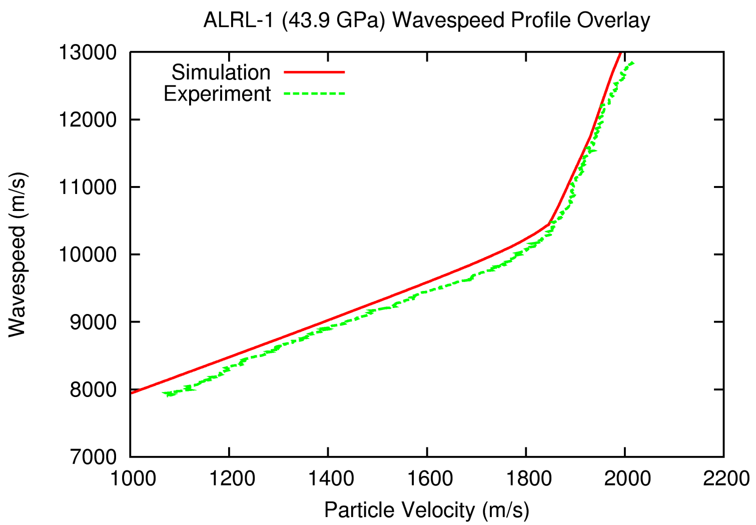
which is a more realistic value for Y at the shocked state.



Example: ALRL-1
σ = 43.9 GPa





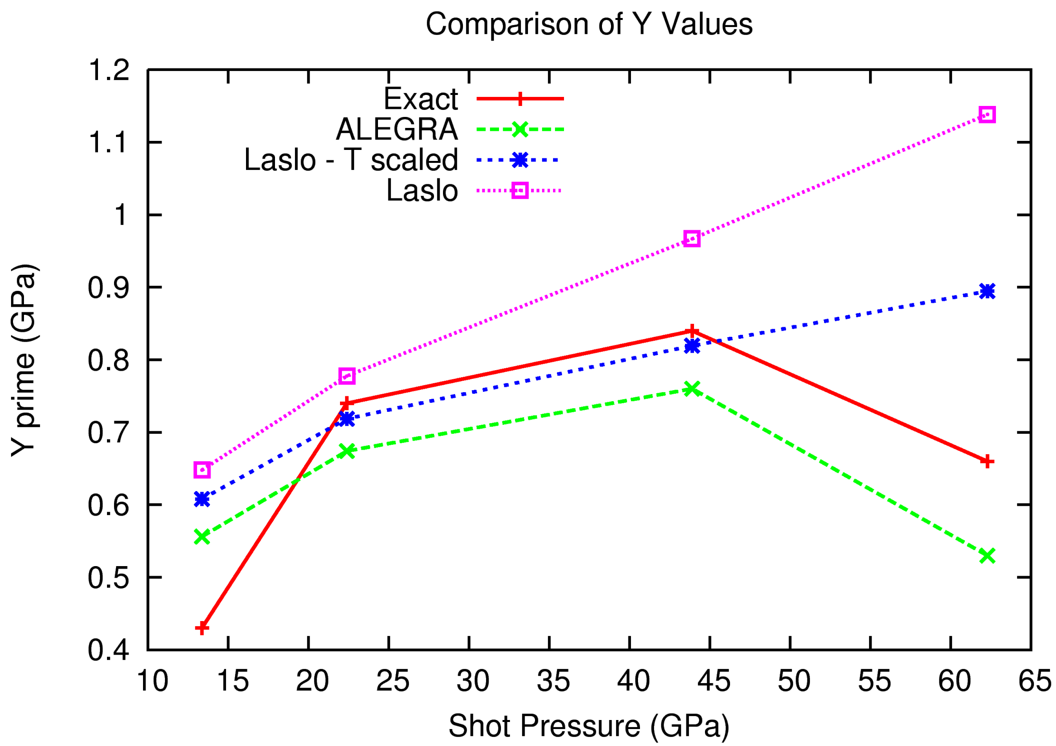


$$\int_0^1 f(\xi)d\xi = 0.201$$

$$Y_{max} = 2.398\text{GPa}$$

$$Y' = 0.963\text{GPa}$$

Comparison of Yield Stress as a Function of Axial Shock Stress



Shot	Temp (K)	Pressure (GPa)	Y'_{exact} (GPa)	Y'_{Laslo} (GPa)	Y'_{Laslo} Temp (GPa)
RL20-4	440	13.36	0.43	0.64	0.61
RL20-3	590	22.39	0.74	0.77	0.72
ALRL-1	1190	43.89	0.84	0.96	0.82
ALRL-2D	1900	62.28	0.66	1.13	0.89

Summary of Results

• The 22 GPa shot shows that if all of the assumption made are justifiable, the process gives good results.

• Contrary to the assumptions made, temperature dependence is not negligible for the higher pressure shots. The next week will be devoted to adding temperature dependence and performing the optimization process again.

• When attempting to extract strength information, operating near the limits of the model's assumptions yields erroneous data.

Conclusions

• The optimization method shows promise of determining Y' (or $\tau_c + \tau_h$) to accuracies characteristic of the 'exact' method by fitting the unloading wave profiles.

• It is believed that the method for determining Y' is independent of the strength model, but additional work is needed.

• Initial simulated wavespeed-particle velocity plots agree well with the analytically generated plots. Further work will be done to assess the feasibility of using this optimization method to determine *in situ* wavespeeds more accurately, especially for ramp loading and large impedance mismatch (Ta/LiF) experiments.

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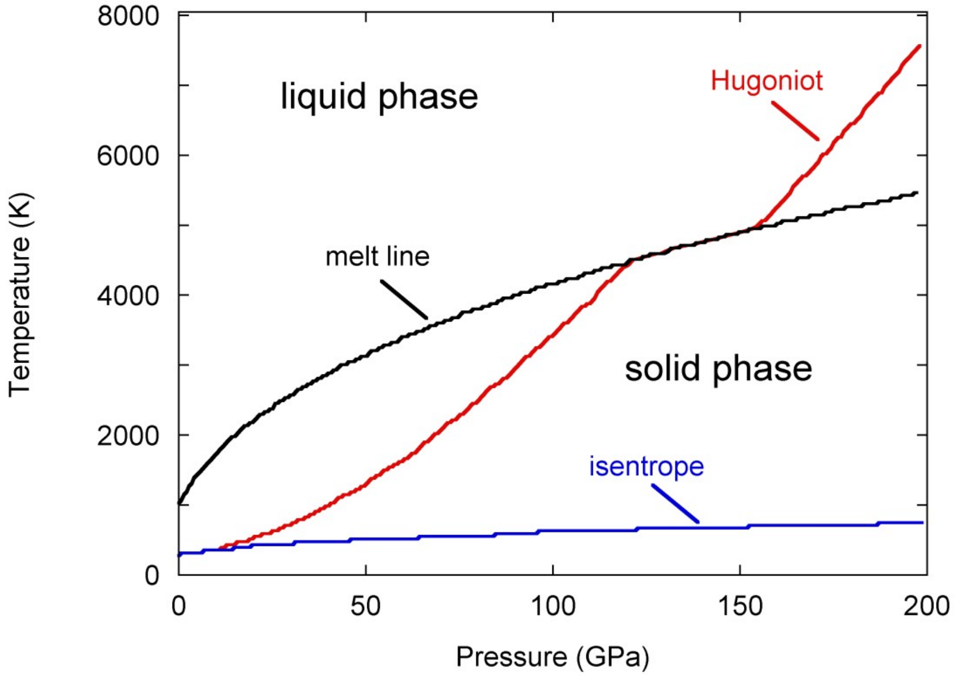
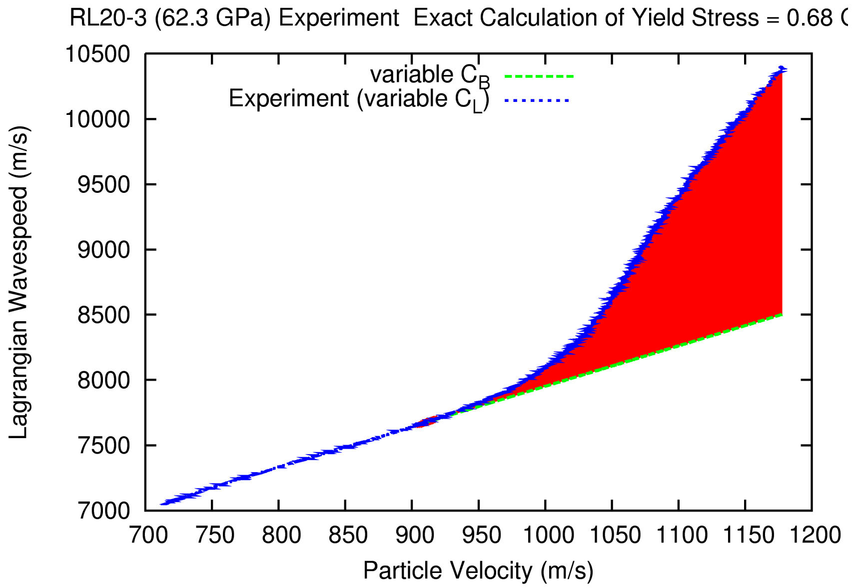
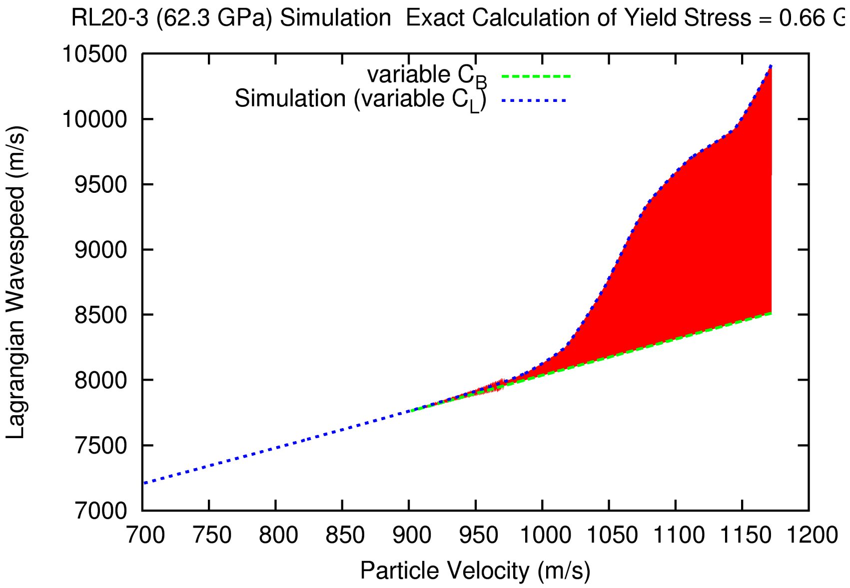
Temperature as a Function of Shock Stress



Comparison of 'Exact' Calculations of Yield Stress





$$dY = \frac{3}{4}\rho_0 \left(C_L^2 - C_B^2\right) \frac{du}{C_L}$$

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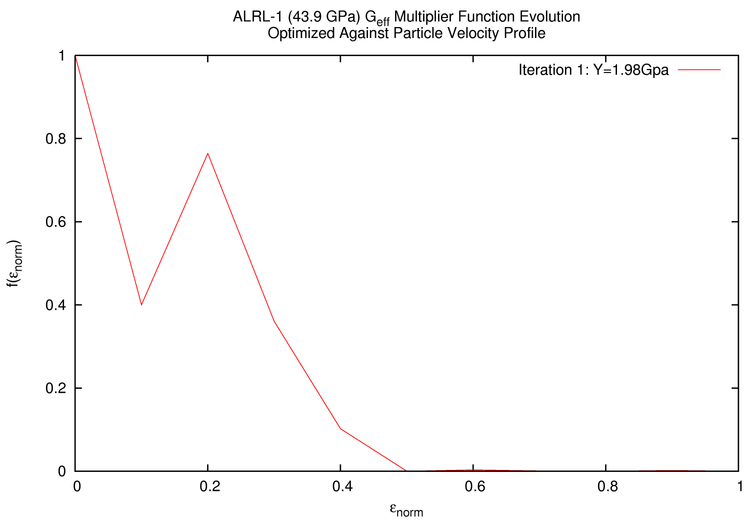

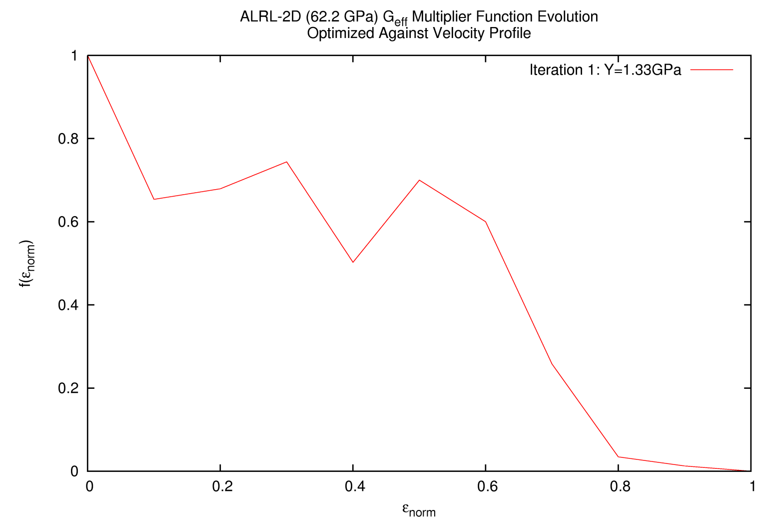

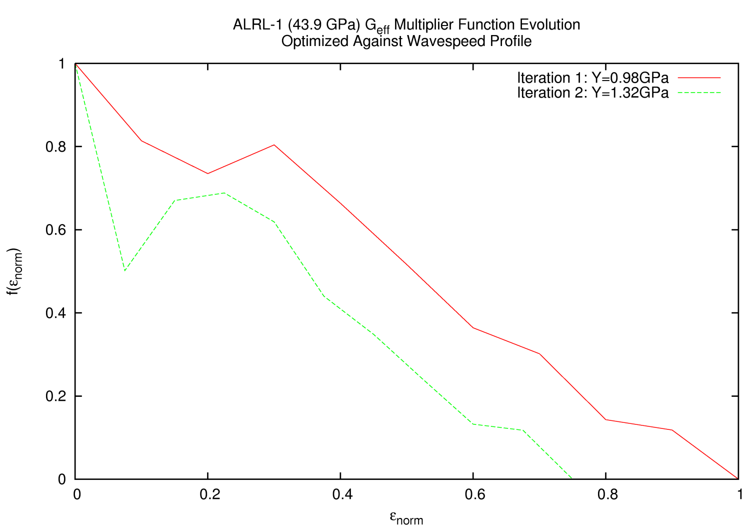

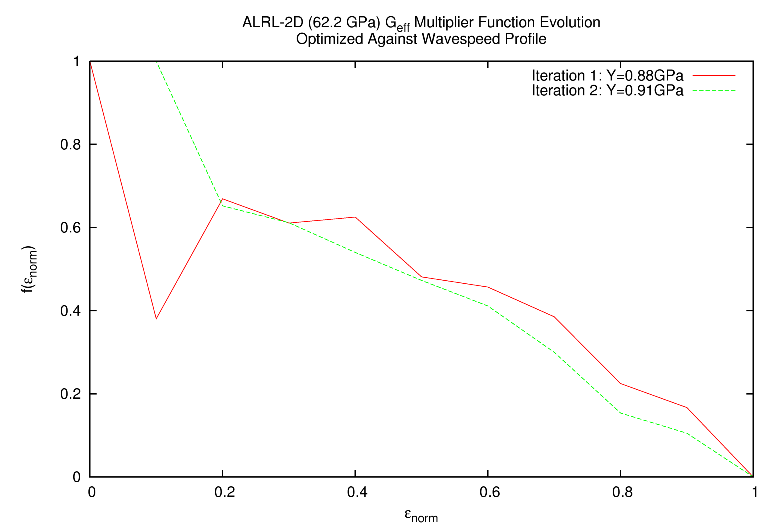

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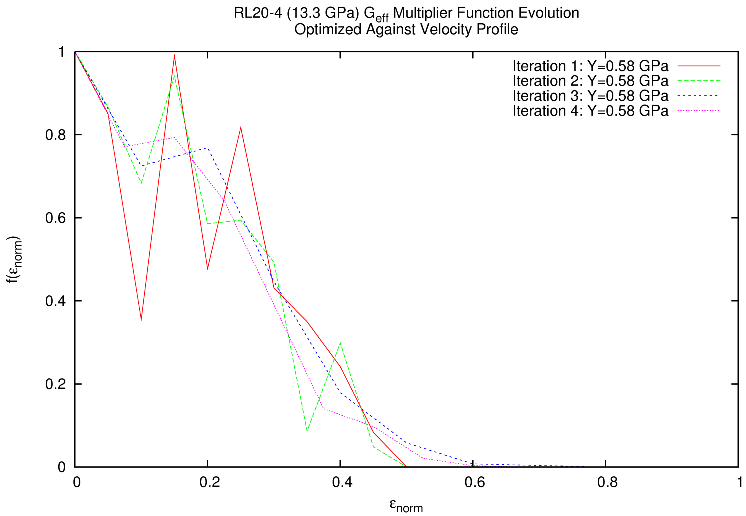
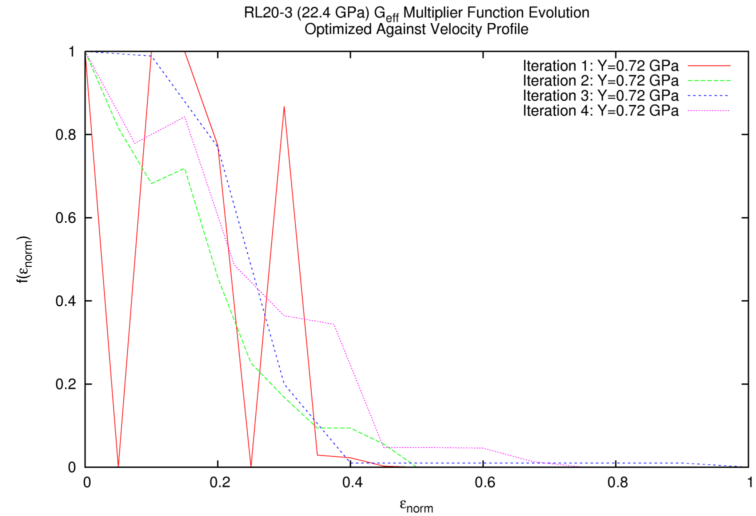
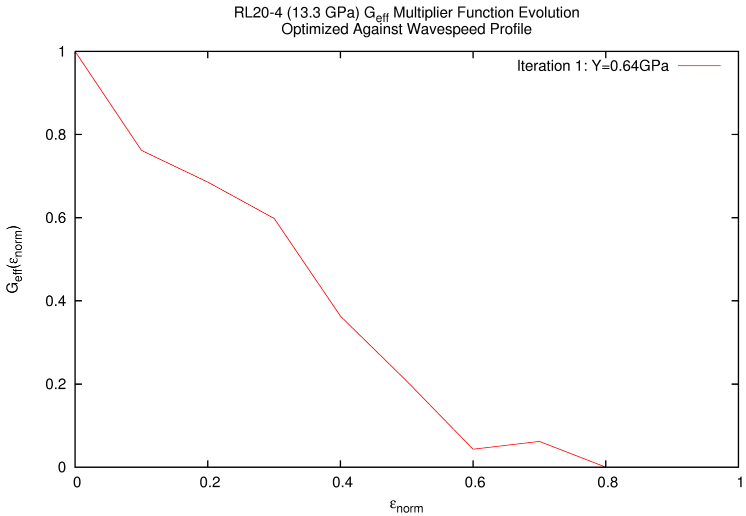

RL20-4 (13.3 GPa) G_{eff} Multiplier Function Evolution
Optimized Against Velocity Profile
Iteration 1: Y=0.58 GPa
Iteration 2: Y=0.58 GPa
Iteration 3: Y=0.58 GPa
Iteration 4: Y=0.58 GPa
$f(\varepsilon_{norm})$
ε_{norm}


RL20-3 (22.4 GPa) G_{eff} Multiplier Function Evolution
Optimized Against Velocity Profile
Iteration 1: Y=0.72 GPa
Iteration 2: Y=0.72 GPa
Iteration 3: Y=0.72 GPa
Iteration 4: Y=0.72 GPa
$f(\varepsilon_{norm})$
ε_{norm}


RL20-4 (13.3 GPa) G_{eff} Multiplier Function Evolution
Optimized Against Wavespeed Profile
Iteration 1: Y=0.64GPa
$G_{eff}(\varepsilon_{norm})$
ε_{norm}