Validation of strain-rate and temperature dependent plasticity models of copper

Biswajit Banerjee

Center for the Simulation of Accidental Fires and Explosions
University of Utah

7th World Conference on Computational Mechanics, 2006
Outline

1. Motivation
   - The Scenario
   - Previous Work

2. Approach

3. Models

4. Model Validation

5. Taylor Impact Simulations

6. Copper Clad Rate Stick Simulations
Outline

1 Motivation
   - The Scenario
   - Previous Work

2 Approach

3 Models

4 Model Validation

5 Taylor Impact Simulations

6 Copper Clad Rate Stick Simulations
Explosive Deformation of a Cylinder

Crushing of a Foam

Uintah Simulations.
Previous Verification and Validation Efforts

- **Common validation tests:**
  - One-dimensional Kolsky bar compression, shear, tension.
  - Taylor impact tests.
  - Flyer plate impact tests.

- **Wilkins and Guinan (1973).**
  - Comparisons of Taylor impact tests with HEMP simulations for "pure" copper.
  - Linear hardening plasticity.

- **Gust (1982).**
  - Comparisons of high-temperature Taylor impact tests with EPIC simulations for ETP copper.
  - Steinberg-Cochran-Guinan model of plasticity.
Previous Verification and Validation Efforts

- **Common validation tests:**
  - One-dimensional Kolsky bar compression, shear, tension.
  - Taylor impact tests.
  - Flyer plate impact tests.

- **Wilkins and Guinan (1973).**
  - Comparisons of Taylor impact tests with HEMP simulations for "pure" copper.
  - Linear hardening plasticity.

- **Gust (1982).**
  - Comparisons of high-temperature Taylor impact tests with EPIC simulations for ETP copper.
  - Steinberg-Cochran-Guinan model of plasticity.
Motivation

Previous Work

Previous Verification and Validation Efforts

- **Common validation tests:**
  - One-dimensional Kolsky bar compression, shear, tension.
  - Taylor impact tests.
  - Flyer plate impact tests.

- Wilkins and Guinan (1973).
  - Comparisons of Taylor impact tests with HEMP simulations for “pure” copper.
  - Linear hardening plasticity.

- Gust (1982).
  - Comparisons of high-temperature Taylor impact tests with EPIC simulations for ETP copper.
  - Steinberg-Cochran-Guinan model of plasticity.
Previous Verification and Validation Efforts

- Common validation tests:
  - One-dimensional Kolsky bar compression, shear, tension.
  - Taylor impact tests.
  - Flyer plate impact tests.

- Wilkins and Guinan (1973).
  - Comparisons of Taylor impact tests with HEMP simulations for “pure” copper.
  - Linear hardening plasticity.

- Gust (1982).
  - Comparisons of high-temperature Taylor impact tests with EPIC simulations for ETP copper.
  - Steinberg-Cochran-Guinan model of plasticity.
Previous Verification and Validation Efforts

- **Common validation tests:**
  - One-dimensional Kolsky bar compression, shear, tension.
  - Taylor impact tests.
  - Flyer plate impact tests.

- **Wilkins and Guinan (1973).**
  - Comparisons of Taylor impact tests with HEMP simulations for "pure" copper.
  - Linear hardening plasticity.

- **Gust (1982).**
  - Comparisons of high-temperature Taylor impact tests with EPIC simulations for ETP copper.
  - Steinberg-Cochran-Guinan model of plasticity.
Previous Verification and Validation Efforts

- Common validation tests:
  - One-dimensional Kolsky bar compression, shear, tension.
  - Taylor impact tests.
  - Flyer plate impact tests.
- Wilkins and Guinan (1973).
  - Comparisons of Taylor impact tests with HEMP simulations for "pure" copper.
  - Linear hardening plasticity.
- Gust (1982).
  - Comparisons of high-temperature Taylor impact tests with EPIC simulations for ETP copper.
  - Steinberg-Cochran-Guinan model of plasticity.
Previous Verification and Validation Efforts

Common validation tests:
- One-dimensional Kolsky bar compression, shear, tension.
- Taylor impact tests.
- Flyer plate impact tests.

Wilkins and Guinan (1973).
- Comparisons of Taylor impact tests with HEMP simulations for “pure” copper.
- Linear hardening plasticity.

Gust (1982).
- Comparisons of high-temperature Taylor impact tests with EPIC simulations for ETP copper.
- Steinberg-Cochran-Guinan model of plasticity.
Previous Verification and Validation Efforts

Common validation tests:
- One-dimensional Kolsky bar compression, shear, tension.
- Taylor impact tests.
- Flyer plate impact tests.

Wilkins and Guinan (1973).
- Comparisons of Taylor impact tests with HEMP simulations for “pure” copper.
- Linear hardening plasticity.

Gust (1982).
- Comparisons of high-temperature Taylor impact tests with EPIC simulations for ETP copper.
- Steinberg-Cochran-Guinan model of plasticity.
Common validation tests:
- One-dimensional Kolsky bar compression, shear, tension.
- Taylor impact tests.
- Flyer plate impact tests.

Wilkins and Guinan (1973).
- Comparisons of Taylor impact tests with HEMP simulations for “pure” copper.
- Linear hardening plasticity.

Gust (1982).
- Comparisons of high-temperature Taylor impact tests with EPIC simulations for ETP copper.
- Steinberg-Cochran-Guinan model of plasticity.
Previous Verification and Validation Efforts

Common validation tests:
- One-dimensional Kolsky bar compression, shear, tension.
- Taylor impact tests.
- Flyer plate impact tests.

Wilkins and Guinan (1973).
- Comparisons of Taylor impact tests with HEMP simulations for “pure” copper.
- Linear hardening plasticity.

Gust (1982).
- Comparisons of high-temperature Taylor impact tests with EPIC simulations for ETP copper.
- Steinberg-Cochran-Guinan model of plasticity.
Previous Verification and Validation Efforts

- **Johnson and Cook (1983, 1985), Johnson and Holmquist (1988).**
  - Comparisons of one-dimensional experimental data with Johnson-Cook model for OFHC copper.
  - Comparisons of Taylor impact tests with EPIC simulations.

- **Zerilli and Armstrong (1987)**
  - Comparisons of one-dimensional experiments and Taylor impact with Zerilli-Armstrong model.
  - Comparison with Johnson-Cook model.

- **Zocher et al. (2000)**
  - Taylor impact tests on OFHC copper compared with simulations using CHAD.
  - Johnson-Cook, Mechanical Threshold Stress, and Steinberg-Cochran-Guinan models compared.
Previous Verification and Validation Efforts

  - Comparisons of one-dimensional experimental data with Johnson-Cook model for OFHC copper.
  - Comparisons of Taylor impact tests with EPIC simulations.

- Zerilli and Armstrong (1987)
  - Comparisons of one-dimensional experiments and Taylor impact with Zerilli-Armstrong model.
  - Comparison with Johnson-Cook model.

- Zocher et al. (2000)
  - Taylor impact tests on OFHC copper compared with simulations using CHAD.
  - Johnson-Cook, Mechanical Threshold Stress, and Steinberg-Cochran-Guinan models compared.
Previous Verification and Validation Efforts

  - Comparisons of one-dimensional experimental data with Johnson-Cook model for OFHC copper.
  - Comparisons of Taylor impact tests with EPIC simulations.

- Zerilli and Armstrong (1987)
  - Comparisons of one-dimensional experiments and Taylor impact with Zerilli-Armstrong model.
  - Comparison with Johnson-Cook model.

- Zocher et al. (2000)
  - Taylor impact tests on OFHC copper compared with simulations using CHAD.
  - Johnson-Cook, Mechanical Threshold Stress, and Steinberg-Cochran-Guinan models compared.
Previous Verification and Validation Efforts

  - Comparisons of one-dimensional experimental data with Johnson-Cook model for OFHC copper.
  - Comparisons of Taylor impact tests with EPIC simulations.

- Zerilli and Armstrong (1987)
  - Comparisons of one-dimensional experiments and Taylor impact with Zerilli-Armstrong model.
  - Comparison with Johnson-Cook model.

- Zocher et al. (2000)
  - Taylor impact tests on OFHC copper compared with simulations using CHAD.
  - Johnson-Cook, Mechanical Threshold Stress, and Steinberg-Cochran-Guinan models compared.
Previous Verification and Validation Efforts

  - Comparisons of one-dimensional experimental data with Johnson-Cook model for OFHC copper.
  - Comparisons of Taylor impact tests with EPIC simulations.

- Zerilli and Armstrong (1987)
  - Comparisons of one-dimensional experiments and Taylor impact with Zerilli-Armstrong model.
  - Comparison with Johnson-Cook model.

- Zocher et al. (2000)
  - Taylor impact tests on OFHC copper compared with simulations using CHAD.
  - Johnson-Cook, Mechanical Threshold Stress, and Steinberg-Cochran-Guinan models compared.
Previous Verification and Validation Efforts

- **Johnson and Cook (1983, 1985), Johnson and Holmquist (1988).**
  - Comparisons of one-dimensional experimental data with Johnson-Cook model for OFHC copper.
  - Comparisons of Taylor impact tests with EPIC simulations.

- **Zerilli and Armstrong (1987)**
  - Comparisons of one-dimensional experiments and Taylor impact with Zerilli-Armstrong model.
  - Comparison with Johnson-Cook model.

- **Zocher et al. (2000)**
  - Taylor impact tests on OFHC copper compared with simulations using CHAD.
  - Johnson-Cook, Mechanical Threshold Stress, and Steinberg-Cochran-Guinan models compared.
Previous Verification and Validation Efforts

- **Johnson and Cook (1983, 1985), Johnson and Holmquist (1988).**
  - Comparisons of one-dimensional experimental data with Johnson-Cook model for OFHC copper.
  - Comparisons of Taylor impact tests with EPIC simulations.

- **Zerilli and Armstrong (1987)**
  - Comparisons of one-dimensional experiments and Taylor impact with Zerilli-Armstrong model.
  - Comparison with Johnson-Cook model.

- **Zocher et al. (2000)**
  - Taylor impact tests on OFHC copper compared with simulations using CHAD.
  - Johnson-Cook, Mechanical Threshold Stress, and Steinberg-Cochran-Guinan models compared.
Previous Verification and Validation Efforts

- **Johnson and Cook (1983, 1985), Johnson and Holmquist (1988).**
  - Comparisons of one-dimensional experimental data with Johnson-Cook model for OFHC copper.
  - Comparisons of Taylor impact tests with EPIC simulations.

- **Zerilli and Armstrong (1987)**
  - Comparisons of one-dimensional experiments and Taylor impact with Zerilli-Armstrong model.
  - Comparison with Johnson-Cook model.

- **Zocher et al. (2000)**
  - Taylor impact tests on OFHC copper compared with simulations using CHAD.
  - Johnson-Cook, Mechanical Threshold Stress, and Steinberg-Cochran-Guinan models compared.
Previous Verification and Validation Efforts

  - Comparisons of one-dimensional experimental data with Johnson-Cook model for OFHC copper.
  - Comparisons of Taylor impact tests with EPIC simulations.

- Zerilli and Armstrong (1987)
  - Comparisons of one-dimensional experiments and Taylor impact with Zerilli-Armstrong model.
  - Comparison with Johnson-Cook model.

- Zocher et al. (2000)
  - Taylor impact tests on OFHC copper compared with simulations using CHAD.
  - Johnson-Cook, Mechanical Threshold Stress, and Steinberg-Cochran-Guinan models compared.
Comments on Previous Work

- No error bars on the experimental data.
- Estimates of accuracy depend on visual examination of the data.
- Some comparison metrics need improvement.
- Comparisons between models are limited.
Comments on Previous Work

- No error bars on the experimental data.
- Estimates of accuracy depend on visual examination of the data.
- Some comparison metrics need improvement.
- Comparisons between models are limited.
Comments on Previous Work

- No error bars on the experimental data.
- Estimates of accuracy depend on visual examination of the data.
- Some comparison metrics need improvement.
- Comparisons between models are limited.
Comments on Previous Work

- No error bars on the experimental data.
- Estimates of accuracy depend on visual examination of the data.
- Some comparison metrics need improvement.
- Comparisons between models are limited.
Outline

1. Motivation
   - The Scenario
   - Previous Work

2. Approach

3. Models

4. Model Validation

5. Taylor Impact Simulations

6. Copper Clad Rate Stick Simulations
We compare five flow stress models for OFHC copper. We simulate one-dimensional tests and estimate the modeling error for each model. We describe a set of metrics for Taylor impact tests. We estimate simulation errors for the Taylor tests. We simulate a copper clad rate-stick and compare surface velocities with experimental data.
Approach

- We compare five flow stress models for OFHC copper.
- We simulate one-dimensional tests and estimate the modeling error for each model.
- We describe a set of metrics for Taylor impact tests.
- We estimate simulation errors for the Taylor tests.
- We simulate a copper clad rate-stick and compare surface velocities with experimental data.
Approach

- We compare five flow stress models for OFHC copper.
- We simulate one-dimensional tests and estimate the modeling error for each model.
- We describe a set of metrics for Taylor impact tests.
- We estimate simulation errors for the Taylor tests.
- We simulate a copper clad rate-stick and compare surface velocities with experimental data.
We compare five flow stress models for OFHC copper.

We simulate one-dimensional tests and estimate the modeling error for each model.

We describe a set of metrics for Taylor impact tests.

We estimate simulation errors for the Taylor tests.

We simulate a copper clad rate-stick and compare surface velocities with experimental data.
We compare five flow stress models for OFHC copper. We simulate one-dimensional tests and estimate the modeling error for each model. We describe a set of metrics for Taylor impact tests. We estimate simulation errors for the Taylor tests. We simulate a copper clad rate-stick and compare surface velocities with experimental data.
Plasticity Model

- We consider pressure, temperature, plastic strain, and strain-rate dependent flow stress models of the form:

\[
\sigma_f = \sigma_Y(\epsilon_p, \dot{\epsilon}, T) \frac{\mu(p, T)}{\mu_0} \tag{1}
\]

- A von-Mises yield condition is assumed:

\[
f := \frac{3}{2} s : s - \sigma_f^2 \leq 0 \tag{2}
\]

- We use an associative rule to determine the plastic flow rate:

\[
d^p = \dot{\gamma} \frac{\partial f}{\partial \sigma} \tag{3}
\]
Plasticity Model

- We consider pressure, temperature, plastic strain, and strain-rate dependent flow stress models of the form

\[ \sigma_f = \sigma_y(\epsilon_p, \dot{\epsilon}, T) \frac{\mu(p, T)}{\mu_0} \]  

(1)

- A von-Mises yield condition is assumed.

\[ f := \frac{3}{2} s : s - \sigma_f^2 \leq 0 \]  

(2)

- We use an associative rule to determine the plastic flow rate.

\[ \dot{d}^p = \dot{\gamma} \frac{\partial f}{\partial \sigma} \]  

(3)
Plasticity Model

- We consider pressure, temperature, plastic strain, and strain-rate dependent flow stress models of the form

\[ \sigma_f = \sigma_y(\epsilon_p, \dot{\epsilon}, T) \frac{\mu(p, T)}{\mu_0} \]  

(1)

- A von-Mises yield condition is assumed.

\[ f := \frac{3}{2} \mathbf{s} : \mathbf{s} - \sigma_f^2 \leq 0 \]  

(2)

- We use an associative rule to determine the plastic flow rate.

\[ \mathbf{d}^p = \dot{\gamma} \frac{\partial f}{\partial \sigma} \]  

(3)
We decompose the Cauchy stress into a volumetric and a deviatoric part.

\[ \sigma = p \mathbf{1} + s \]  

The pressure is computed using a Mie-Gruneisen EOS. The deviatoric stress is computed using a hypoelastic rate equation

\[ \dot{s} = 2 \mu(p, T) (d - d^p) \]  

We use a modified form of a plastic predictor-elastic corrector algorithm (Nemat-Nasser, 1991; Maudlin and Schiferl, 1996).
We decompose the Cauchy stress into a volumetric and a deviatoric part.

\[ \sigma = p \mathbf{1} + \mathbf{s} \]  

(4)

The pressure is computed using a Mie-Gruneisen EOS. The deviatoric stress is computed using a hypoelastic rate equation

\[ \mathbf{s} = 2 \mu(p, T) (\mathbf{d} - \mathbf{d}^p) \]  

(5)

We use a modified form of a plastic predictor-elastic corrector algorithm (Nemat-Nasser, 1991; Maudlin and Schiferl, 1996).
We decompose the Cauchy stress into a volumetric and a deviatoric part.

\[ \sigma = p \mathbf{1} + \mathbf{s} \] (4)

The pressure is computed using a Mie-Gruneisen EOS. The deviatoric stress is computed using a hypoelastic rate equation

\[ \dot{s} = 2 \mu(p, T) (d - d^p) \] (5)

We use a modified form of a plastic predictor-elastic corrector algorithm \(^{\text{Nemat-Nasser, 1991; Maudlin and Schiferl, 1996}}\).
The material point method is used to discretize the governing equations in space. (Sulsky et al., 1994, 1995; Bardenhagen et al, 2001; Bardenhagen and Kober, 2004).

For high rate processes, a forward Euler algorithm is used for time discretization with a semi-implicit stress update.

For quasistatic processes, an fully implicit backward Euler algorithm is used for all time discretizations.
Solution Algorithm

- The material point method is used to discretize the governing equations in space. (Sulsky et al., 1994, 1995; Bardenhagen et al., 2001; Bardenhagen and Kober, 2004).

- For high rate processes, a forward Euler algorithm is used for time discretization with a semi-implicit stress update.

- For quasistatic processes, an fully implicit backward Euler algorithm is used for all time discretizations.
Solution Algorithm

- The material point method is used to discretize the governing equations in space. (Sulsky et al., 1994, 1995; Bardenhagen et al., 2001; Bardenhagen and Kober, 2004).

- For high rate processes, a forward Euler algorithm is used for time discretization with a semi-implicit stress update.

- For quasistatic processes, an fully implicit backward Euler algorithm is used for all time discretizations.
Outline

1. Motivation
   - The Scenario
   - Previous Work

2. Approach

3. Models

4. Model Validation

5. Taylor Impact Simulations

6. Copper Clad Rate Stick Simulations
Flow Stress Models

- **Steinberg-Cochran-Guinan-Lund model** (Steinberg et al., 1980; Steinberg and Lund, 1989).
  - Semi-Empirical and high rates.
- **Mechanical Threshold Stress model** (Follansbee and Kocks, 1988; Goto et al., 2000).
  - Physically-based but for rates < $10^7$ /s.
- **Preston-Tonks-Wallace model** (Preston et al., 2003).
  - Physically-based and a large range of rates, including overdriven shocks. $C^0$ continuous.
Flow Stress Models

- **Steinberg-Cochran-Guinan-Lund model** (Steinberg et al., 1980; Steinberg and Lund, 1989).
  Semi-Empirical and high rates.

- **Mechanical Threshold Stress model** (Follansbee and Kocks, 1988; Goto et al., 2000).
  Physically-based but for rates $< 10^7$ /s.

- **Preston-Tonks-Wallace model** (Preston et al., 2003).
  Physically-based and a large range of rates, including overdriven shocks. $C^0$ continuous.
Steinberg-Cochran-Guinan-Lund model (Steinberg et al., 1980; Steinberg and Lund, 1989).
Semi-Empirical and high rates.

Mechanical Threshold Stress model (Follansbee and Kocks, 1988; Goto et al., 2000).
Physically-based but for rates $< 10^7 \, /s$.

Preston-Tonks-Wallace model (Preston et al., 2003).
Physically-based and a large range of rates, including overdriven shocks. $C^0$ continuous.
Other Models

Shear modulus models:
- Guinan-Steinberg model (Guinan and Steinberg, 1975; Steinberg et al., 1980).
  Pressure and temperature dependent but empirical.
  Temperature dependence based on physical grounds.
  Pressure dependence uses Guinan-Steinberg model.

Melting temperature models:
- Steinberg-Cochran-Guinan model (Steinberg et al., 1980).
  Pressure-dependent. Empirical.
- Burakovsky-Preston-Silbar model (Burakovsky et al., 2000).
  Physically-based.

Empirical specific heat model.
Other Models

- **Shear modulus models:**
  - **Guinan-Steinberg model** (Guinan and Steinberg, 1975; Steinberg et al., 1980). Pressure and temperature dependent but empirical.

- **Melting temperature models:**
  - **Steinberg-Cochran-Guinan model** (Steinberg et al., 1980). Pressure-dependent. Empirical.
  - **Burakovsky-Preston-Silbar model** (Burakovsky et al., 2000). Physically-based.

- Empirical specific heat model.
Other Models

- Shear modulus models:
  - Guinan-Steinberg model (Guinan and Steinberg, 1975; Steinberg et al., 1980).
    Pressure and temperature dependent but empirical.
    Temperature dependence based on physical grounds.
    Pressure dependence uses Guinan-Steinberg model.

- Melting temperature models:
  - Steinberg-Cochran-Guinan model (Steinberg et al., 1980).
    Pressure-dependent. Empirical.
  - Burakovsky-Preston-Silbar model. (Burakovsky et al., 2000).
    Physically-based.

- Empirical specific heat model.
Other Models

- **Shear modulus models:**
  - Guinan-Steinberg model (Guinan and Steinberg, 1975; Steinberg et al., 1980). Pressure and temperature dependent but empirical.

- **Melting temperature models:**

- Empirical specific heat model.
Other Models

- **Shear modulus models:**
  - Guinan-Steinberg model \(\text{(Guinan and Steinberg, 1975; Steinberg et al., 1980)}\).
    Pressure and temperature dependent but empirical.
  - Nadal-LePoac model \(\text{(Nadal and LePoac, 2003)}\).
    Temperature dependence based on physical grounds.
    Pressure dependence uses Guinan-Steinberg model.

- **Melting temperature models:**
  - Steinberg-Cochran-Guinan model \(\text{(Steinberg et al., 1980)}\).
    Pressure-dependent. Empirical.
  - Burakovsky-Preston-Silbar model \(\text{(Burakovsky et al., 2000)}\).
    Physically-based.

  Empirical specific heat model.
Other Models

- **Shear modulus models:**
  - Guinan-Steinberg model \((\text{Guinan and Steinberg, 1975; Steinberg et al., 1980})\).
    Pressure and temperature dependent but empirical.
  - Nadal-LePoac model \((\text{Nadal and LePoac, 2003})\).
    Temperature dependence based on physical grounds. Pressure dependence uses Guinan-Steinberg model.

- **Melting temperature models:**
  - Steinberg-Cochran-Guinan model \((\text{Steinberg et al., 1980})\).
    Pressure-dependent. Empirical.
  - Burakovsky-Preston-Silbar model \((\text{Burakovsky et al., 2000})\).
    Physically-based.

- Empirical specific heat model.
Other Models

- **Shear modulus models:**
  - Guinan-Steinberg model (Guinan and Steinberg, 1975; Steinberg et al., 1980).
    Pressure and temperature dependent but empirical.
    Temperature dependence based on physical grounds.
    Pressure dependence uses Guinan-Steinberg model.

- **Melting temperature models:**
  - Steinberg-Cochran-Guinan model (Steinberg et al., 1980).
    Pressure-dependent. Empirical.
  - Burakovsky-Preston-Silbar model. (Burakovsky et al., 2000).
    Physically-based.

- **Empirical specific heat model.**
Outline

1. Motivation
   • The Scenario
   • Previous Work

2. Approach

3. Models

4. Model Validation

5. Taylor Impact Simulations

6. Copper Clad Rate Stick Simulations
Shear Modulus, Melt Temperature, Specific Heat

(a) Shear modulus.

NP: Mean Err. = -1.8 %
Std. Dev. Err. = 1.7 %

GS: Mean Err. = 2.6 %
Std. Dev. Err. = 1.5 %

(b) Melt temperature.

SCG: Mean Err. = -0.3 %
Std. Dev. Err. = 3.0 %

BPS: Mean Err. = 2.2 %
Std. Dev. Err. = 3.7 %

(c) Specific heat.

Mean Err. = -0.1 %
Std. Dev. Err. = 1.1 %
Steinberg-Cochran-Guinan-Lund Model

Condition | Average Max. Error (%) |
---|---|
All Tests | 64 |
Tension Tests | 20 |
Compression Tests | 126 |
High Strain-rate ($\geq 100 \text{ /s}$) | 22 |
Low Strain-rate ($< 100 \text{ /s}$) | 219 |
High Temperature ($\geq 800 \text{ K}$) | 90 |
Low Temperature ($< 800 \text{ K}$) | 20 |
Mechanical Threshold Stress Model

- **OFHC Copper (Mechanical Threshold Stress)**
  - 8000/s, 296K
  - 2300/s, 873K
  - 1800/s, 1023K
  - 960/s, 1173K
  - 0.066/s, 1173K
  - 4000/s, 77K
  - 4000/s, 496K
  - 4000/s, 696K
  - 4000/s, 896K
  - 4000/s, 1096K

- **Condition Average Max. Error (%)**
  - All Tests: 23
  - Tension Tests: 14
  - Compression Tests: 35
  - High Strain-rate (≥ 100 /s): 15
  - Low Strain-rate (< 100 /s): 49
  - High Temperature (≥ 800 K): 27
  - Low Temperature (< 800 K): 15
## Preston-Tonks-Wallace Model

### OFHC Copper (Preston–Tonks–Wallace)

- **8000/s, 296K**
- **0.1/s, 296K**
- **2300/s, 873K**
- **1800/s, 1023K**
- **960/s, 1173K**
- **0.066/s, 1173K**

### OFHC Copper (PTW)

- **4000/s, 1096K**
- **4000/s, 77K**
- **4000/s, 496K**
- **4000/s, 696K**
- **4000/s, 896K**
- **4000/s, 1096K**

### Condition Average Max. Error (%)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Average Max. Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Tests</td>
<td>17</td>
</tr>
<tr>
<td>Tension Tests</td>
<td>18</td>
</tr>
<tr>
<td>Compression Tests</td>
<td>10</td>
</tr>
<tr>
<td>High Strain-rate (≥ 100 /s)</td>
<td>18</td>
</tr>
<tr>
<td>Low Strain-rate (&lt; 100 /s)</td>
<td>5</td>
</tr>
<tr>
<td>High Temperature (≥ 800 K)</td>
<td>16</td>
</tr>
<tr>
<td>Low Temperature (&lt; 800 K)</td>
<td>14</td>
</tr>
</tbody>
</table>
Outline

1. Motivation
   - The Scenario
   - Previous Work

2. Approach

3. Models

4. Model Validation

5. Taylor Impact Simulations

6. Copper Clad Rate Stick Simulations
Validation Metrics

(a) Validation metrics

(b) Final Length/Initial Length

(c) Final Diameter/Initial Diameter

(d) Final Volume/Initial Volume

Wilkins and Guinan (1973)
Gust (1982)
Gust (ETP) (1982)
Johnson and Cook (1983)
Jones et al. (1987)
House et al. (1995)
Simulated

Biswajit Banerjee (University of Utah)

Validation of Plasticity Models
Final Profile: $T = 298$ K
Error Metrics: $T = 298$ K

% Error = \( \frac{\text{Sim.}}{\text{Expt.}} - 1 \times 100 \)

![Bar chart showing error metrics for different models.](image-url)
Final Profile: $T = 1235$ K

- SCGL
- MTS
- PTW
Copper Clad Rate Stick Simulations

Outline

1 Motivation
   • The Scenario
   • Previous Work

2 Approach

3 Models

4 Model Validation

5 Taylor Impact Simulations

6 Copper Clad Rate Stick Simulations

Biswajit Banerjee (University of Utah)
Copper Clad Rate Stick Simulations

Deformation of Copper Cladding

Linear Hardening Model.
30 cm Long Rate Stick. QM100 explosive.
JWL++ EOS. (Courtesy: Jim Guilkey)

Preston-Tonks-Wallace Model.
40 cm Long Rate Stick. QM100 explosive.
JWL++ EOS.
Surface Velocity Profiles

Linear Hardening Model.
Expt. data at 30 cm. Sim. data at 25 cm.
(Courtesy: Jim Guilkey)

Preston-Tonks-Wallace Model.
Expt. data at 30 cm. Sim. data at 7 cm.
We have found that the Preston-Tonks-Wallace model provides the best match to experimental data.

- We have quantified some modeling errors.
- A major challenge is how to incorporate model uncertainties into large simulations.
We have found that the Preston-Tonks-Wallace model provides the best match to experimental data.

We have quantified some modeling errors.

A major challenge is how to incorporate model uncertainties into large simulations.
We have found that the Preston-Tonks-Wallace model provides the best match to experimental data.

We have quantified some modeling errors.

A major challenge is how to incorporate model uncertainties into large simulations.
B. Banerjee. An evaluation of plastic flow stress models for the simulation of high-temperature and high-strain-rate deformation of metals

B. Banerjee. Taylor impact tests: Detailed report
For Further Reading II

J. E. Guilkey, T. B. Harman, B. Banerjee
An Eulerian-Lagrangian approach for simulating explosions of energetic devices