Dynamic Strength of Metals Under Extreme Conditions

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Motivation


Elastic Precursor- indicator of material strength

Melt point of 99.999% pure Al – 933.4 K

Growth in HEL (dynamic strength under uniaxial strain) under extreme dynamic loading conditions at test temperatures approaching melt
Elevated Temperature Plate Impact Experiments: Challenges

- Major experimental challenges arise because of the introduction of heating elements in the impact chamber.
- Require remote tilt adjustment tools to compensating for loss in parallelism of the target/flyer due to differential thermal expansion of components in the target holder assembly.
- For oblique plate experiments need to extend combined NDI and TDI to elevated temperatures. Need holographic grating that can withstand elevated temperatures. Also, the bounding target plates need to remain elastic at the elevated temperatures.

OUR APPROACH: Design experiments such that the flyer plate on the sabot represents the specimen -- heat the flyer on the sabot and not the target plate.
Modifications to the Gas Gun

Extension to the gun barrel to incorporate the heater assembly

High pressure Chamber

3.25 inch dia. gun barrel with key way
Modifications to the Gas Gun

- Power supply and thermocouple feedthrough
- Heater stem with 4” of axial reach and full rotational freedom
- Inconel heater element mounted on an alumina insulative housing
- Detail A
- High Pressure Breech
- Heated sabot design
- Out to Impact Chamber
Sabot Design to Carry the Heated Flyer plate

Aluminum body
- $k = 240 \text{ W/(m-K)}$
- Thermal expansion $13 \mu$-strain/$^\circ$C

Alumina silicate -- Lava-rock (fired)
- Working Temp $2000^\circ$F
- Density $\sim 3 \text{ Kg/m}^3$
- Thermal conductivity $= 2 \text{ W/(m-K)}$
- Thermal expansion $1.95 \mu$strain/$^\circ$C
New Instrumentation for Combined Normal and Transverse Particle Displacement Measurements

**Normal Motion Diagnostics**
- System Bandwidth 3.795GHz
- Maximum Velocity 2.9km/s

**Transverse Motion Diagnostics**
- System Bandwidth *3.795GHz
- Currently 350 MHz (400m/s)

Peak to peak variation in light intensity

\[ \text{NDI} \quad \frac{\lambda}{2} \sim 0.75\mu m \]
\[ \text{TDI} \quad \frac{1}{2p} \sim 1\mu m \]
Reverse Geometry Normal Plate Impact with heated flyer plates

Tungsten Carbide
Purity: 99.9%
Melting point: 2800 °C

Aluminum (fcc)
Purity: 99.9999%
Melting point: 660.4 °C

Magnesium (hcp)
Purity: 99.9%
Melting point: 649 °C

\[ \sigma_T(t^n) = \rho_T C_{LT} \frac{1}{1 + \frac{C_{LT}}{C}} V_{fs}(t^n) \]

\[ \rho_F C_F = \frac{\rho_T C_T V_{sp}}{(1 + \frac{C_T}{C_{LT}}) V_o - V_{fs}} \]
Aluminum 99.999% Purity (Polycrystalline)

Lower velocities at the initial rise in particle velocity and at the shock plateau with increasing initial sample (flyer plate) temperature.
Revealed lower shock impedance with increasing initial sample temperature, except for the highest test temperature case, and lower shock impedance in pre-test annealed samples.
As-received vs. Annealed (Al 99.9999% Purity)

Room Temperature Normal Plate Impact
Heated Flyer: Commercial Purity (99.999%) Al
Elastic Target: Inconel 718 Alloy

Room Temp Effect of Grain size
As-received
RIAL061 (as-received)
304 μm avg. grain size
23°C, 98 m/s

Annealed
PHAL068 (annealed) (60 min at 600°C)
1.6 mm avg. grain size
23°C, 110 m/s

PHAL069 (annealed) (30 min at 600°C)
1.11 mm avg. grain size
23°C, 109 m/s
**EBSD (Al 99.9999% Purity)**

**As-Received**
(Extrusion direction)

- Grain size: Avg. 304 μm; spread 17 to 565 μm
- High grain-orientation spread
- Lots of low-angle grain boundary (high residual stresses)

**Annealed**
(600°C for 30 min)

- Grain size: Avg. 1.11 mm; spread 17 μm to 1.429 mm
- Lower grain orientation spread.
- Texture development in the 100 direction
SEM Post-test Specimens (Al 99.9999% Purity)
Magnesium 99.9% Purity: EBSD

As-received at room temperature

Annealed at 600°C for 60 min

As-received c axis -- along radial direction

Annealed. c axis rotates from radial to extrusion direction
Once again we observe lower shock impedance with increasing initial sample temperature, except for the highest test temperature case.
Magnesium 99.9% Purity (Polycrystalline)
Magnesium 99.9% Purity (Polycrystalline)
For the highest test temperature case (630 °C) we notice the re-immergence of twin bands in post-shocked samples.
Possible Mechanisms

Strength of the Material

\[ \tau = \tau_1 + \tau_2 = \frac{G}{G_o} \left( \tau^* + \frac{U_o}{v^*} \right) - \frac{KT}{v^*} \ln \left( \frac{NAbv_m}{\dot{\gamma}} \right) + \tau_2 \]

Thermally activated process of overcoming potential Barriers

Viscous drag provided by the interaction between moving dislocations and phonons (lattice waves)

At very high strain rates and temperatures approaching melt

\[ \dot{\gamma} = bNv_m; \quad v_m = \frac{L}{t_1 + t_2} \approx \frac{L}{t_2} \quad \text{t}_2 \gg \text{t}_1 \text{ as } \dot{\gamma} \uparrow \text{ and/or } T \uparrow \]

\[ t_1 = \frac{1}{\omega_o} \exp \left( \frac{\Delta G(\tau)}{KT} \right); \quad t_2 = \frac{B^* L}{\tau b} \]

where \[ B^* = \frac{B(T)}{1 - \frac{v_m^2}{c_s^2}} \quad B \uparrow \text{ as } T \uparrow \]

\[ \tau \approx \tau_2 = \frac{B(T)\dot{\gamma}}{bN \left[ 1 - \frac{v_m^2}{c_s^2} \right]} \]

Strength of the material is dominated by viscous drag
Current Work: Dynamic Shearing Resistance of Metals Near their Melt Temperatures Using Pressure-shear Configuration

\[
\begin{align*}
\sigma(t) &= \frac{(\rho c_l)_{\text{tar}}}{2} V_{fs}(t) \\
\tau(t) &= \frac{(\rho c_s)_{\text{tar}}}{2} U_{fs}(t) \\
\dot{\gamma}_p(t) &= \frac{2(\rho c_s)_{\text{flyer}}}{(\rho c_s)_{\text{flyer}} + (\rho c_s)_{\text{tar}}} \frac{U_o - U_{fs}}{h} \\
\gamma_p &= \int_0^t \dot{\gamma}_p(t) dt
\end{align*}
\]
Reverse geometry plate impact experiments on tungsten carbide reveal lower shock impedance of the heated flyer plate with temperature.
Student Training and Collaborations

Ph.D. Students:
• Bryan Zuanetti
• Tianxue Wang

Publications:

In Progress:
Bryan Zuanetti – Guest Student at LANL (Summer 2017)

- Laser induced Shock Experiments - Cindy Bolme, Shawn McGrane
- Crystal Plasticity Modeling - DJ Luscher, Frank Addessio

Measurements of elastic precursor amplitudes through thin aluminum films subjected to laser induced shock revealed growth in the HEL with temperatures in the range of 23 – 400 °C
Student Training and Collaborations

Bryan Zuanetti – Dynamic Compression Summer School (Argon National Lab) (Summer 2017)
Thank you!
**Additional Information**

Sample Temperature:

\[ T_1 < T_2 \]

\[ c_f^{(3)}(T_2) < c_f^{(3)}(T_1) \]