Department of Mechanical and Aerospace Engineering, North Carolina State University, September 9th, 2016

SAND2016-8241PE

Exceptional service in the national interest

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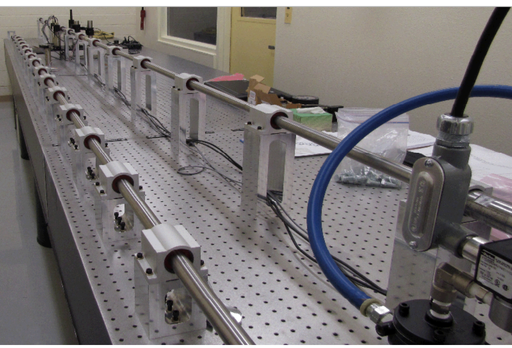
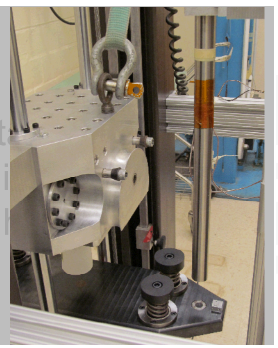
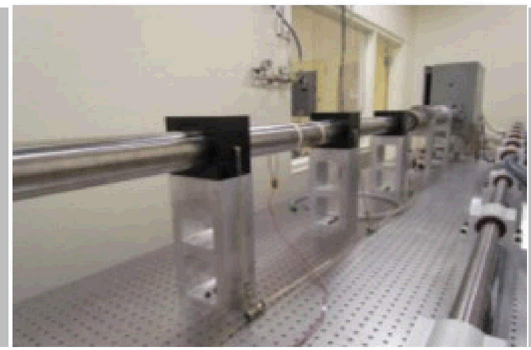
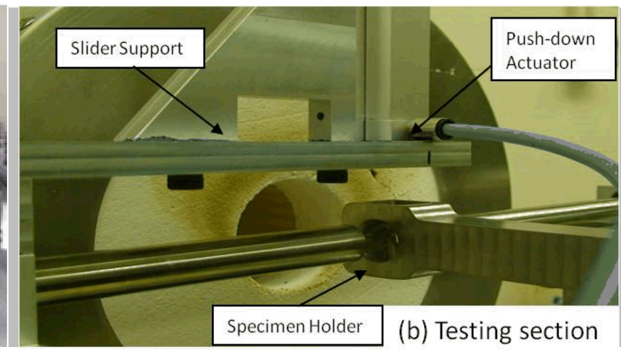

ENGINEERING SCIENCES CENTER

High-Temperature Split Hopkinson (Kolsky) Bar Techniques

Bo Song

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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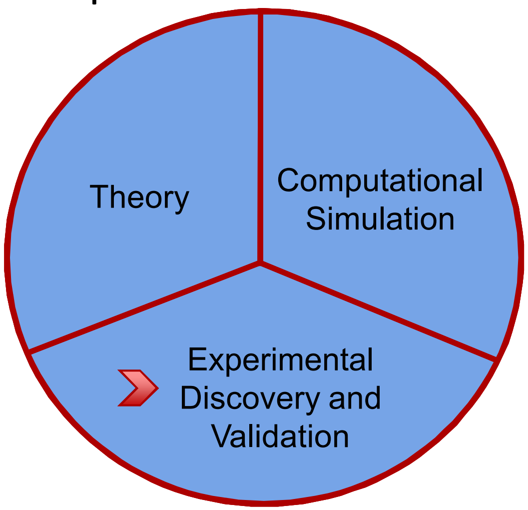
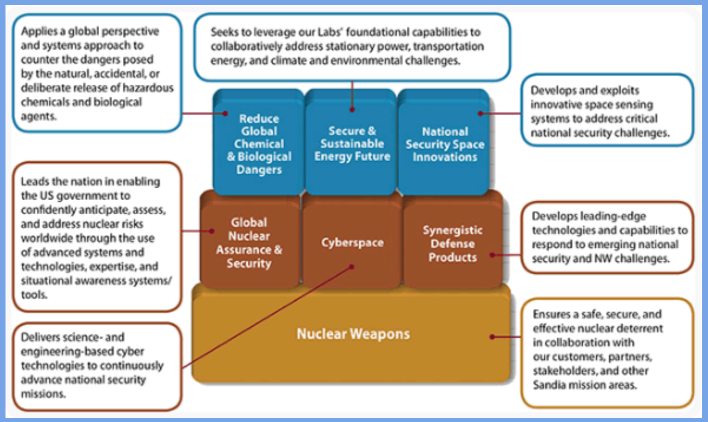
Engineering Sciences Center (1500)

Sandia National Laboratories

- **Center 1500: Engineering Sciences Center**
  - Navigating a Path to the Future
  - Transforming Engineering Sciences through advancing, integrating and applying out technical capabilities to serve the nation

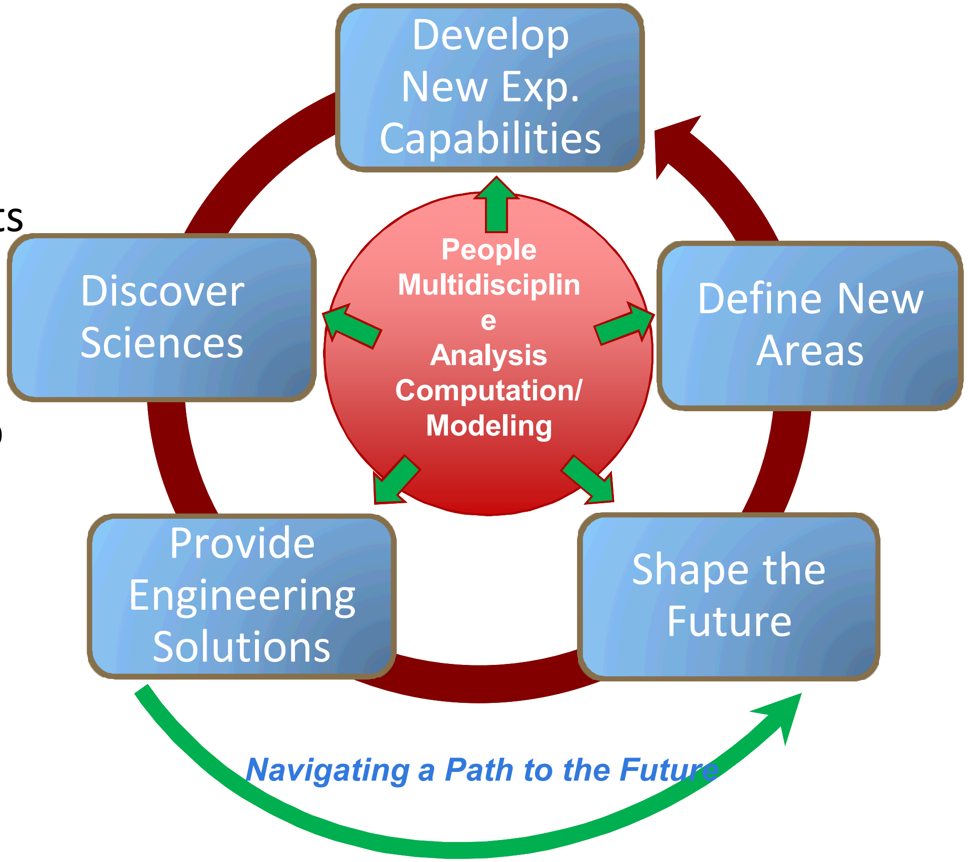


  - Groups
    - Thermal, Fluid & Aero Sciences (1510)
    - Structural Dynamics (1520)
    - Validation and Qualification (1530)
    - Computational Simulation (1540)
    - Solid Mechanics and Shock Physics (1550)



Structural Dynamics Group (1520)

- **Research-Development-Application (R-D-A) Spectrum**
  - Application-driven R&D
  - Analysis guided experiments
  - Computation integrated experiments
- **R-D-A Areas**
  - Mechanical Shock Lab
  - Experimental Impact Mechanics Lab
  - Structural Mechanics Lab
  - Vibration and Acoustic Lab
  - Non-destructive Evaluation Lab
  - Climatic and Centrifuge Lab
  - Component Dynamics Lab
  - Radiography Lab
  - Structural Dynamics Lab



Experimental Solid Mechanics (1528)

Structural Mechanics Lab.

Servo-hydraulic Testing Machines, Pressure Testing Cage

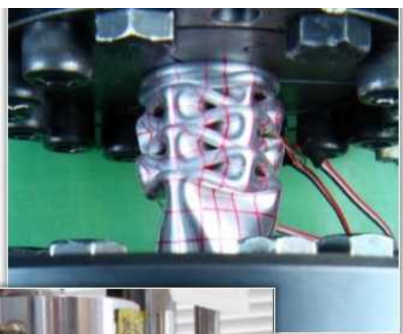
Mechanical Shock Lab.

Drop Tables; Slide Table;

Resonant Beam/Plate; Package Tester

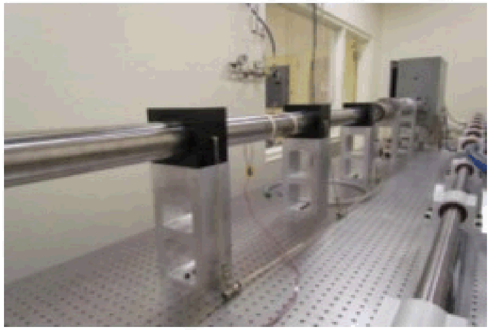
Experimental Impact Mechanics Lab

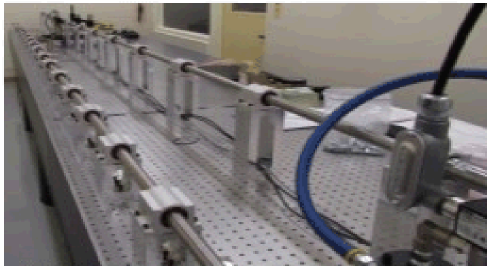
Split Hopkinson Bars, Dropkinson Bar



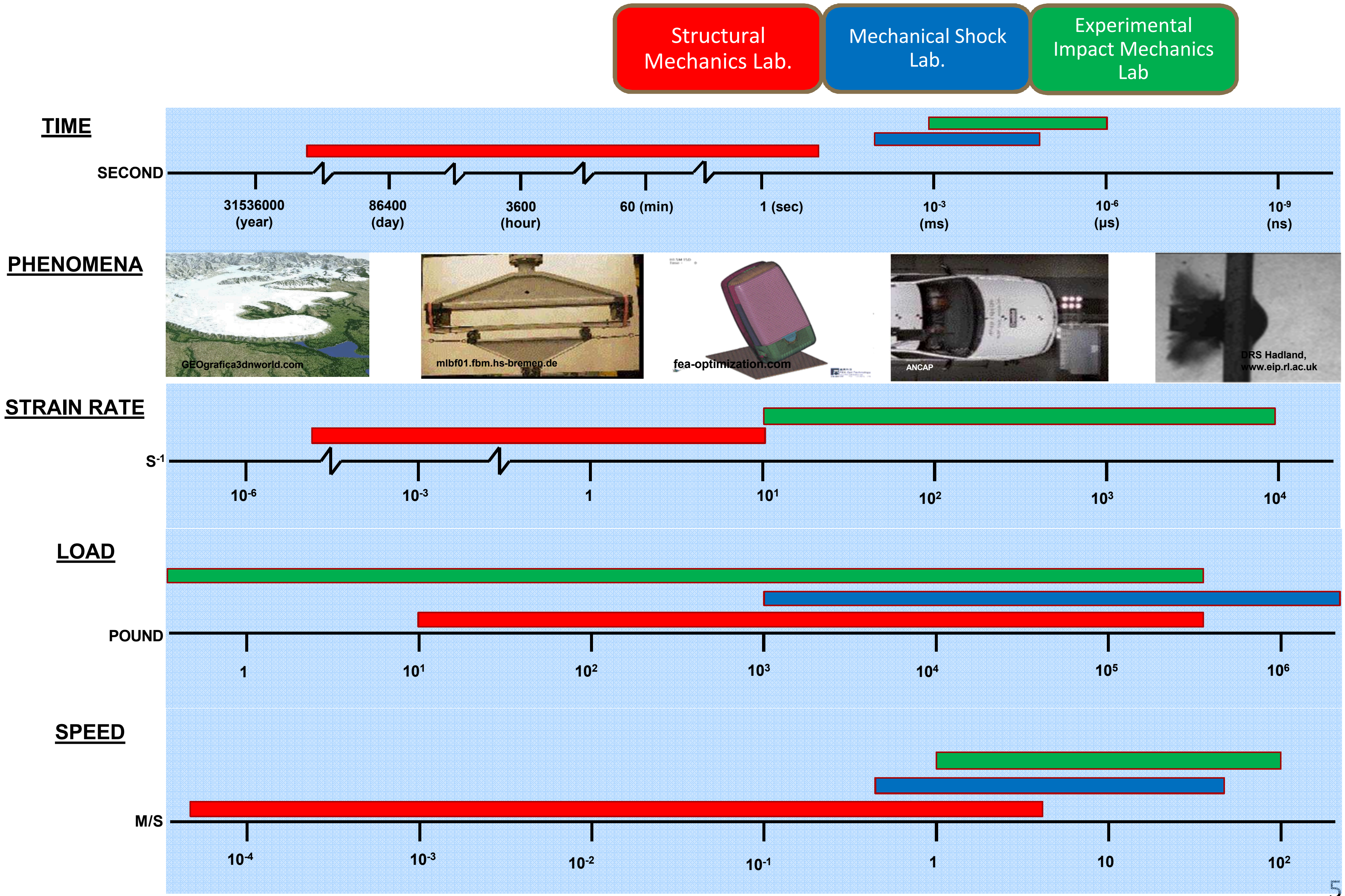
Buckling mode study of thin walled tubes

Standard cylindrical test specimen instrumented with strain gages and an extensometer walled tubes

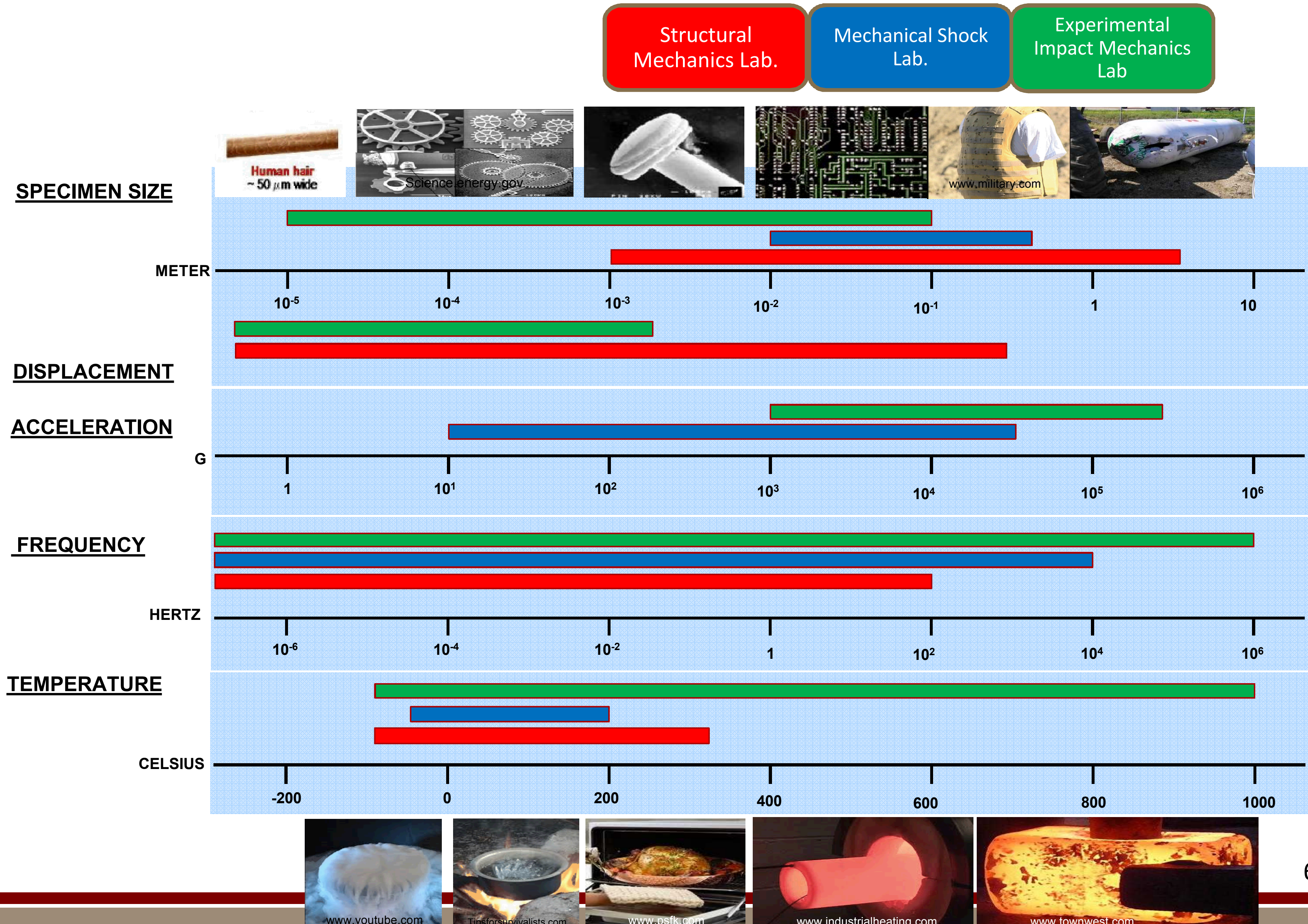




Experimental Solid Mechanics Capabilities



Experimental Solid Mechanics Capabilities



Experimental Impact Mechanics Lab. (EIML)

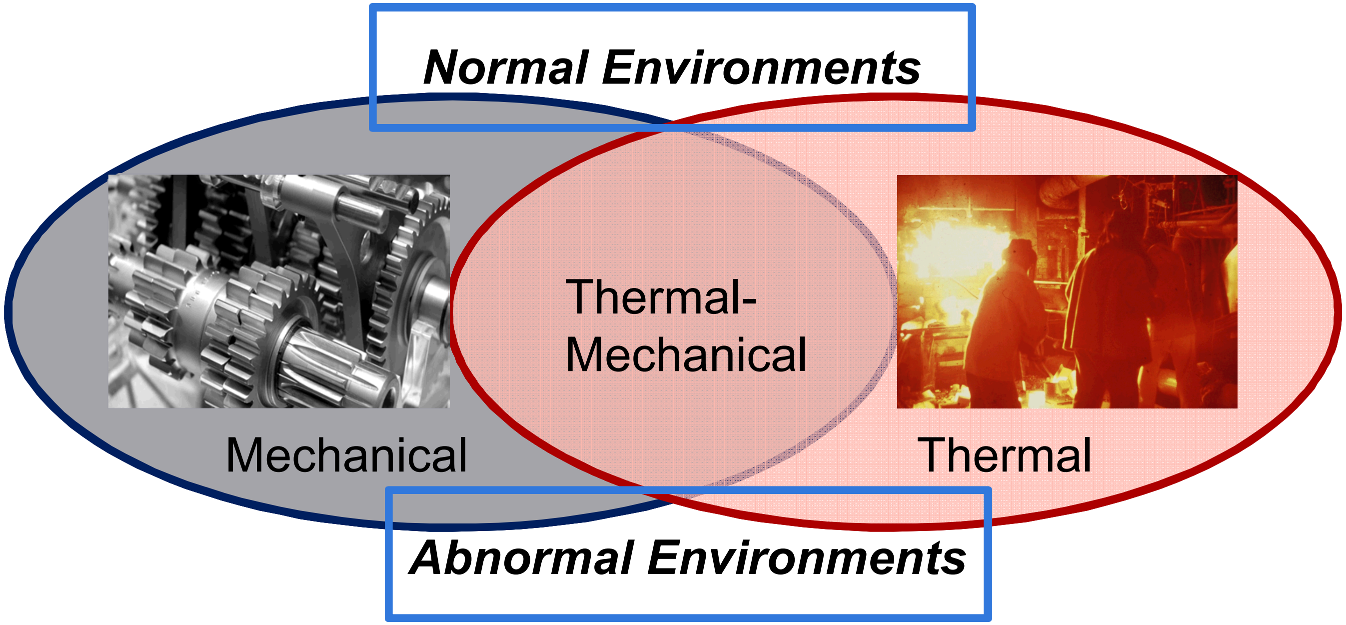
Sandia National Laboratories

- Facilities:
  - *1"-diameter split Hopkinson compression bar (Kolsky compression bar)*
  - *1"-diameter split Hopkinson tension bar (Kolsky tension bar)*
  - *1"-diameter "dropkinson" bar for intermediate-rate tensile testing*
  - *3"-diameter split Hopkinson compression bar (Kolsky compression bar)*

- Capabilities
  - **Dynamic Characterization of Materials**
    - *Dynamic stress-strain response of materials in compression or tension (shear coming soon)*
    - *Dynamic failure and fracture of materials*
    - *Strain-rate Range: ~100 – 10,000 s^{-1}*
    - ***Temperature Range: -100 – 1200^{o}C***
    - *Stress state: uniaxial stress; triaxial stress (in compression only)*
    - *Materials covered: ceramics, alloys, composites, glasses, polymers, foams, biological tissues, concretes, sands, soil, etc*

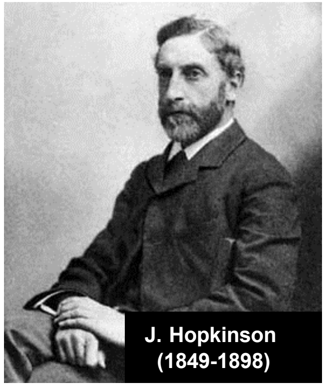
  - **Dynamic Characterization of Component/Small Structures**
    - *Dynamic structural testing with preload capability (compression or tension)*
    - *Wave Propagation/Interaction*
    - *Shock Mitigation*
    - *Dynamic Interface Problem*
    - *Component/Device Functionality/Survivability in Abnormal Mechanical Environments*
      - *High-g, high-frequency impact and vibration*
    - *Impact Sensor characterization*
  - **Rate-dependent Model Validation**
    - *High rate, high frequency, etc*

Abnormal Thermal-Mechanical Environments

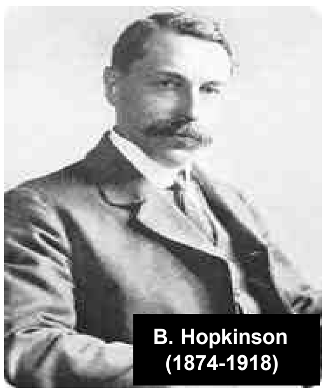


- **Manufacturing Process**
- **Failure/Fracture Analysis**

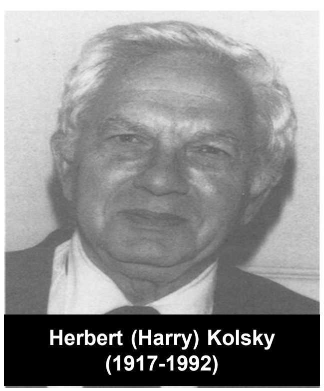
Split Hopkinson (Kolsky) Bar



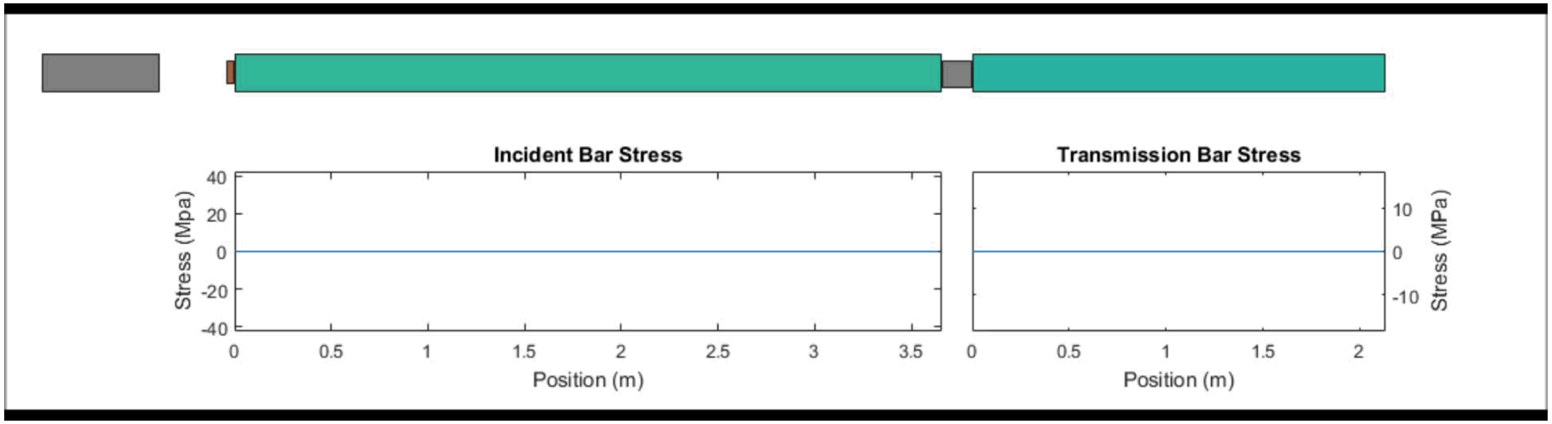
J. Hopkinson (1849-1898)



B. Hopkinson (1874-1918)



Herbert (Harry) Kolsky (1917-1992)



Mass Conservation

$$V_1 = C_0(\varepsilon_i - \varepsilon_r)$$

$$V_2 = C_0 \varepsilon_t$$

$$\dot{\varepsilon} = \frac{V_1 - V_2}{l_s} = \frac{C_0}{l_s}(\varepsilon_i - \varepsilon_r - \varepsilon_t)$$

$$\varepsilon = \int_0^t \dot{\varepsilon}(\tau) d\tau$$

Momentum Conservation

$$F_1 = E_0 A_0 (\varepsilon_i + \varepsilon_r)$$

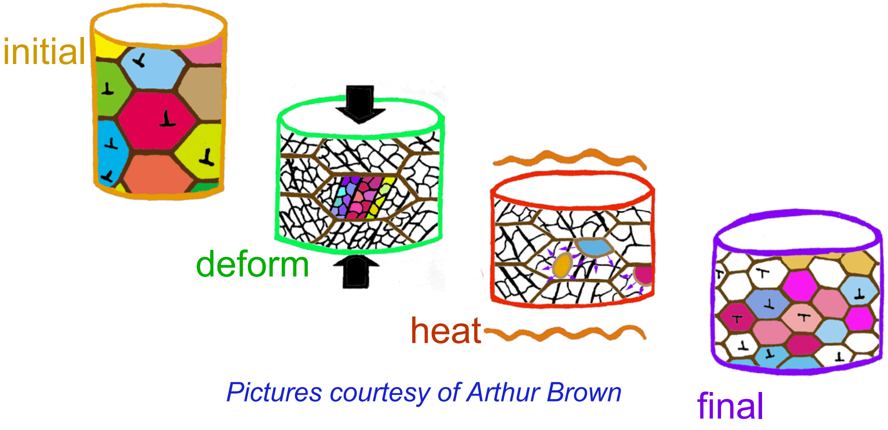
$$F_2 = E_0 A_0 \varepsilon_t$$

$$\sigma = \frac{F_1 + F_2}{2A_s} = \frac{E_0 A_0}{2A_s}(\varepsilon_i + \varepsilon_r + \varepsilon_t)$$

$$\sigma \sim \varepsilon$$

High-Temperature Split Hopkinson (Kolsky) Compression Bar Experiments on 304L Stainless Steel for Recrystallization Investigation

Recrystallization is the process by which the dislocation structure in a worked material is wiped away by growth of nuclei that form a new, relatively dislocation-free set of grains



Pictures courtesy of Arthur Brown

- **Material Property Change**
  - Reduction in material strength and hardness
  - Increase in ductility

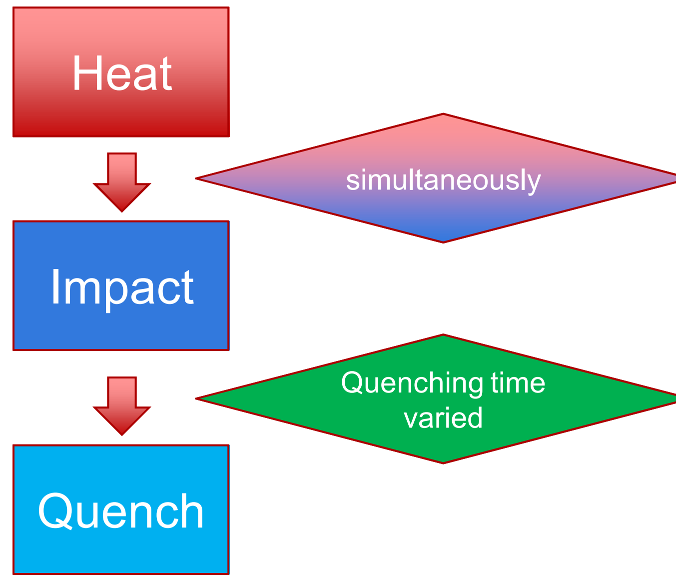
High-Temperature Split Hopkinson (Kolsky) Compression Bar for Forging

Experimental Design for Simulating Forging Process

Forging is a manufacturing process involving the shaping of metal using localized compressive forces

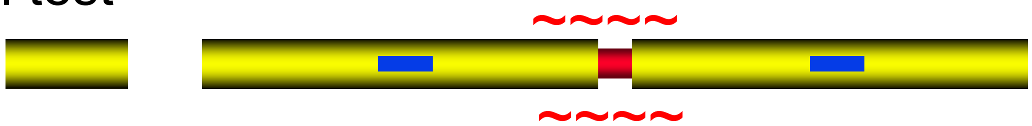
- Temperature – cold, warm, hot
- Drop forging - hammer is raised and then "dropped" onto the workpiece to deform it according to the shape of the die.


www.wikipedia.org

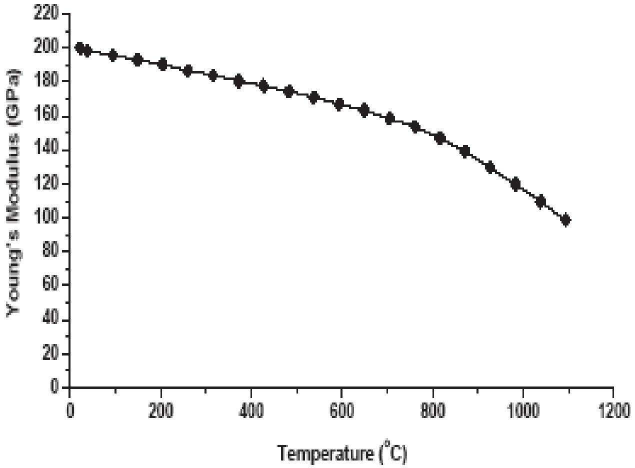


High-Temperature Kolsky Compression Bar

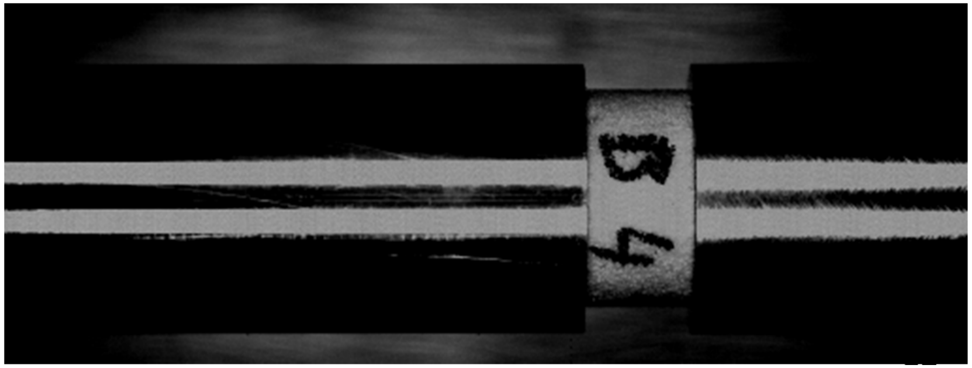
- High-temperature mechanical test
  - Hot Specimen/Cold Bars



  - Heat transfer
    - Specimen temperature drops
    - Bar temperature increases – thermal gradient in the bars
  - Cold Contact Time (CCT)
    - is the time during which the “hot” specimen stays in contact with the “cold” pressure bars until being dynamically loaded
    - should be as short as possible (~ milliseconds)



- Quenching
  - Ensure a single loading on the specimen
  - Maintain the same constant temperature of the specimen before quenched
  - Control the time duration (seconds to minutes) between dynamic testing and quenching



High Temperature Impact Test

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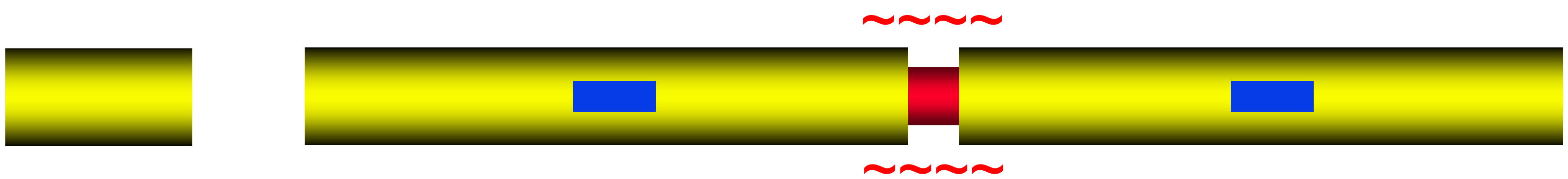
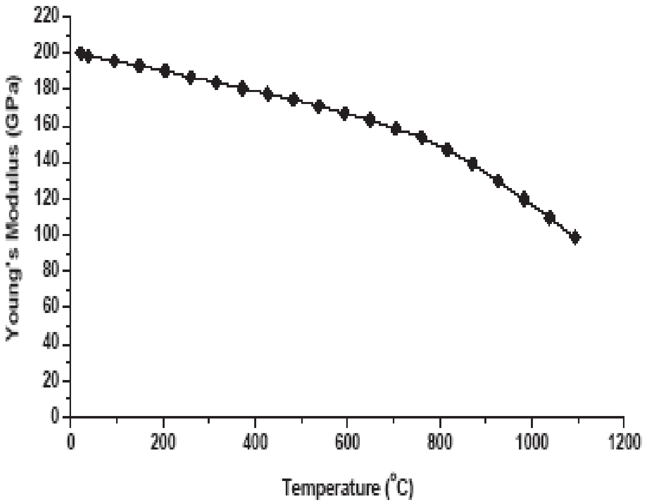


- Kolsky bar for high temperature compression test
  - Heat specimen and bar ends
    - Hot specimen
    - Thermal gradient in the bars

$$\dot{\varepsilon} = \frac{u_1 - u_2}{l_0} = \frac{\dot{C}_0}{l_0}(\varepsilon_i - \varepsilon_r - \varepsilon_t) \qquad \varepsilon = \int_0^t \dot{\varepsilon}(t)dt$$

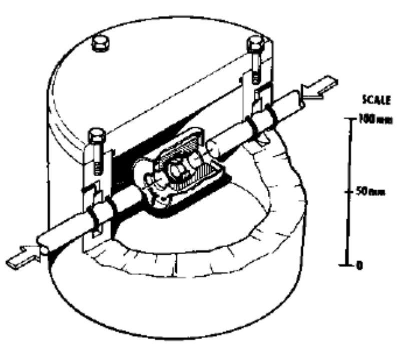
$$\sigma = \frac{F_1 - F_2}{2A_0} = \frac{E_b A_b}{2A_0}(\varepsilon_i + \varepsilon_r + \varepsilon_t)$$



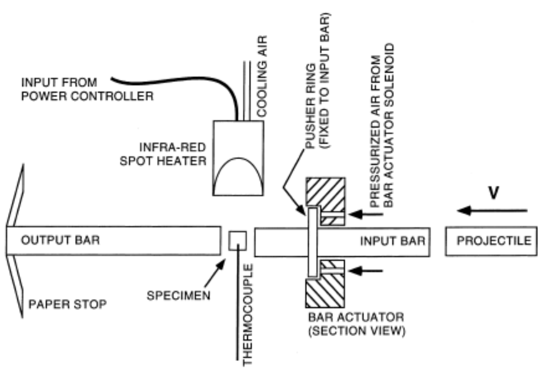
  - Heat specimen individually
    - Hot specimen
    - Cold bars

High-Temperature Kolsky Compression bar

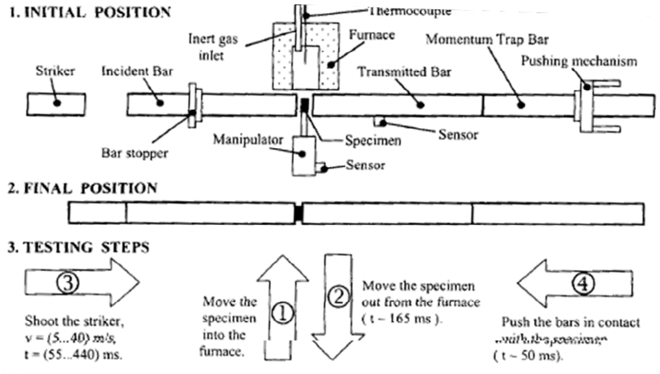
- Hot Specimen/Cold Bars
  - Heat transfer
    - Specimen temperature drops
    - **Bar temperature increases – thermal gradient in the bars**
  - Cold Contact Time (CCT)
    - is the time during which the "hot" specimen stays in contact with the "cold" pressure bars until being dynamically loaded
    - should be as short as possible
      - ~ milliseconds



(Frantz et al. 1984)



(Lennon and Ramesh, 1998)



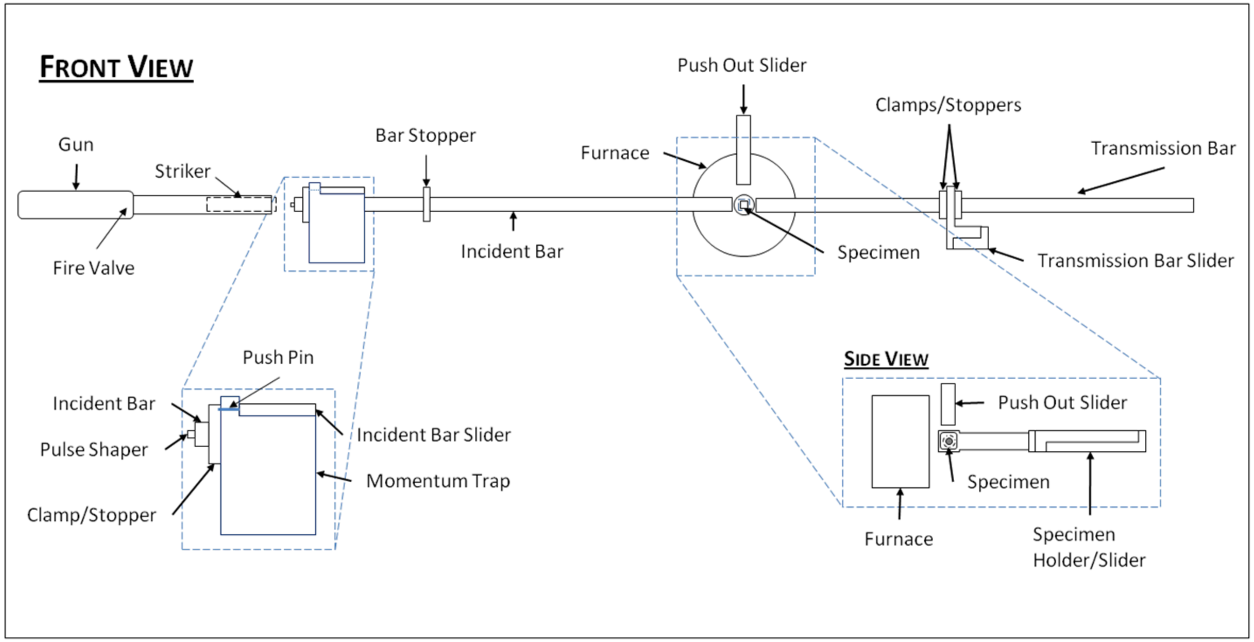
(Apostol et al. 2003)

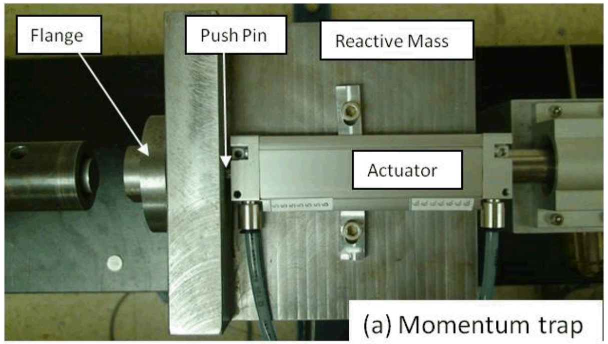
High-Temperature Kolsky Bar at SNL

- We followed Kuokkola's design (Apostol et al. 2003) but made modifications for recrystallization investigation
  - Mechanical Test: ensure single loading on the specimen
    - Momentum trap is applied
  - After Mechanical Test: control of quenching process
    - **Temperature control**
      - Reheat the specimen after impact
        - Maintain constant temperature before the specimen is quenched into water
    - **Time control**
      - Precise time control since the specimen is dynamically loaded until being quenched into water
  - **Investigation of structure-property relationship**
    - Microstructure observation and measurement
    - **Mechanical properties measurement of the dynamically loaded specimens**

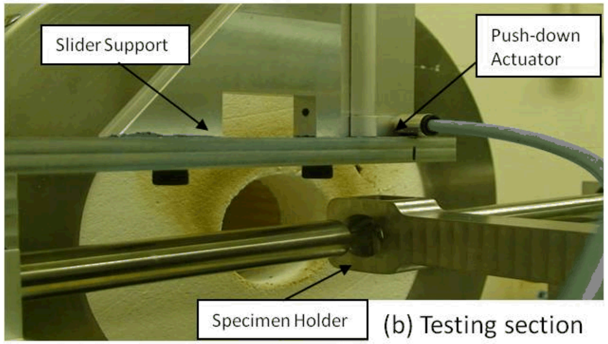
High-Temperature Kolsky Bar at SNL

Sandia National Laboratories

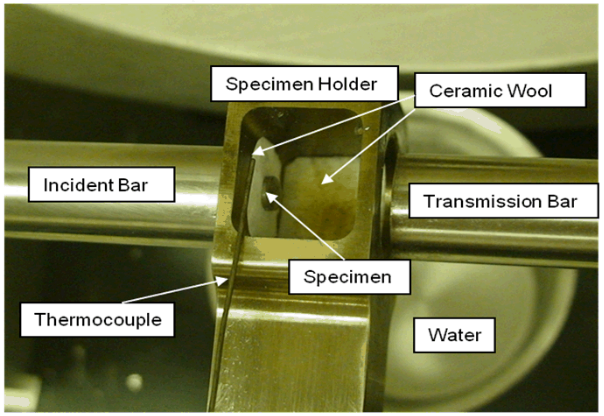




(a) Momentum trap



(b) Testing section



Operation Procedure

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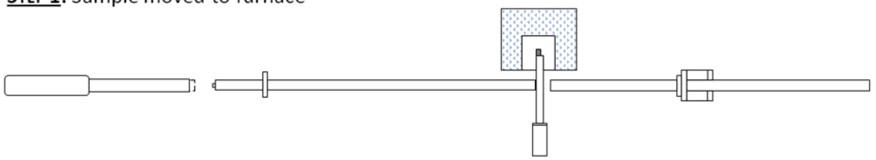
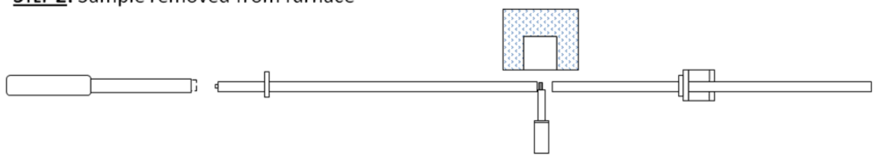
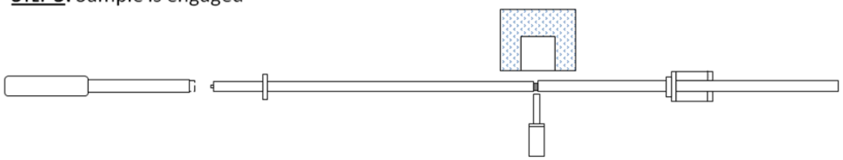
Step 1: Sample moved to furnace



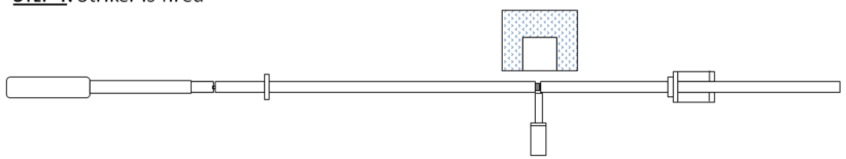
Step 2: Sample removed from furnace



Step 3: Sample is engaged

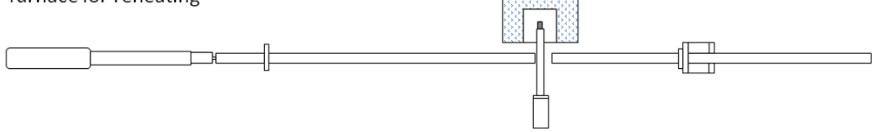


Step 4: Striker is fired

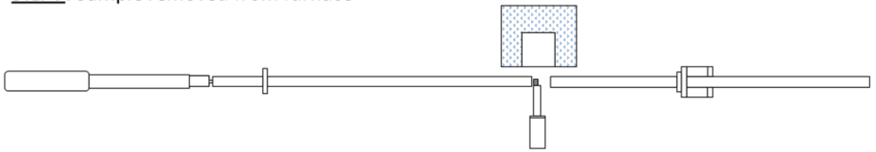


Step 5: Bars are moved away from sample

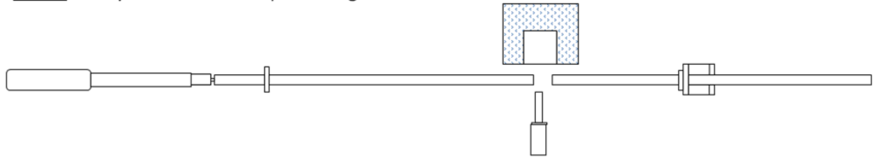
Step 6: Sample moved back to furnace for reheating



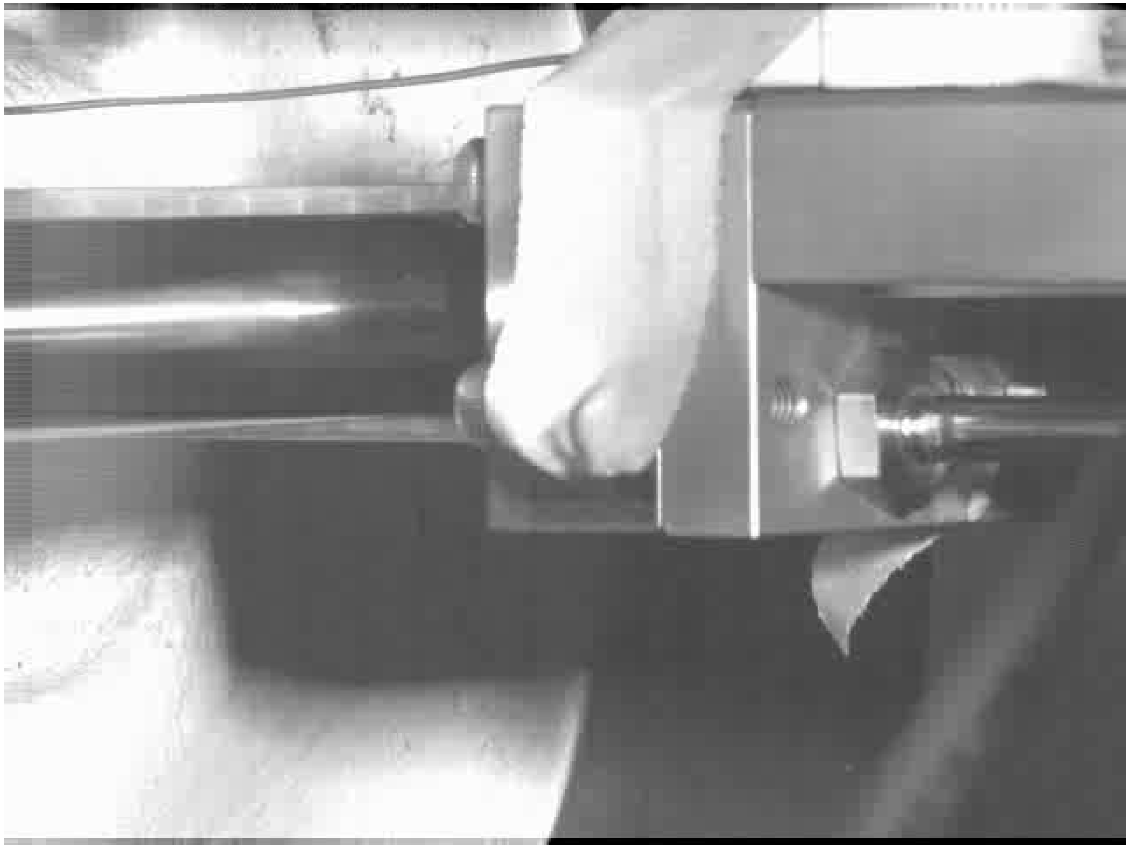
Step 7: Sample removed from furnace



Step 8: Sample released for quenching

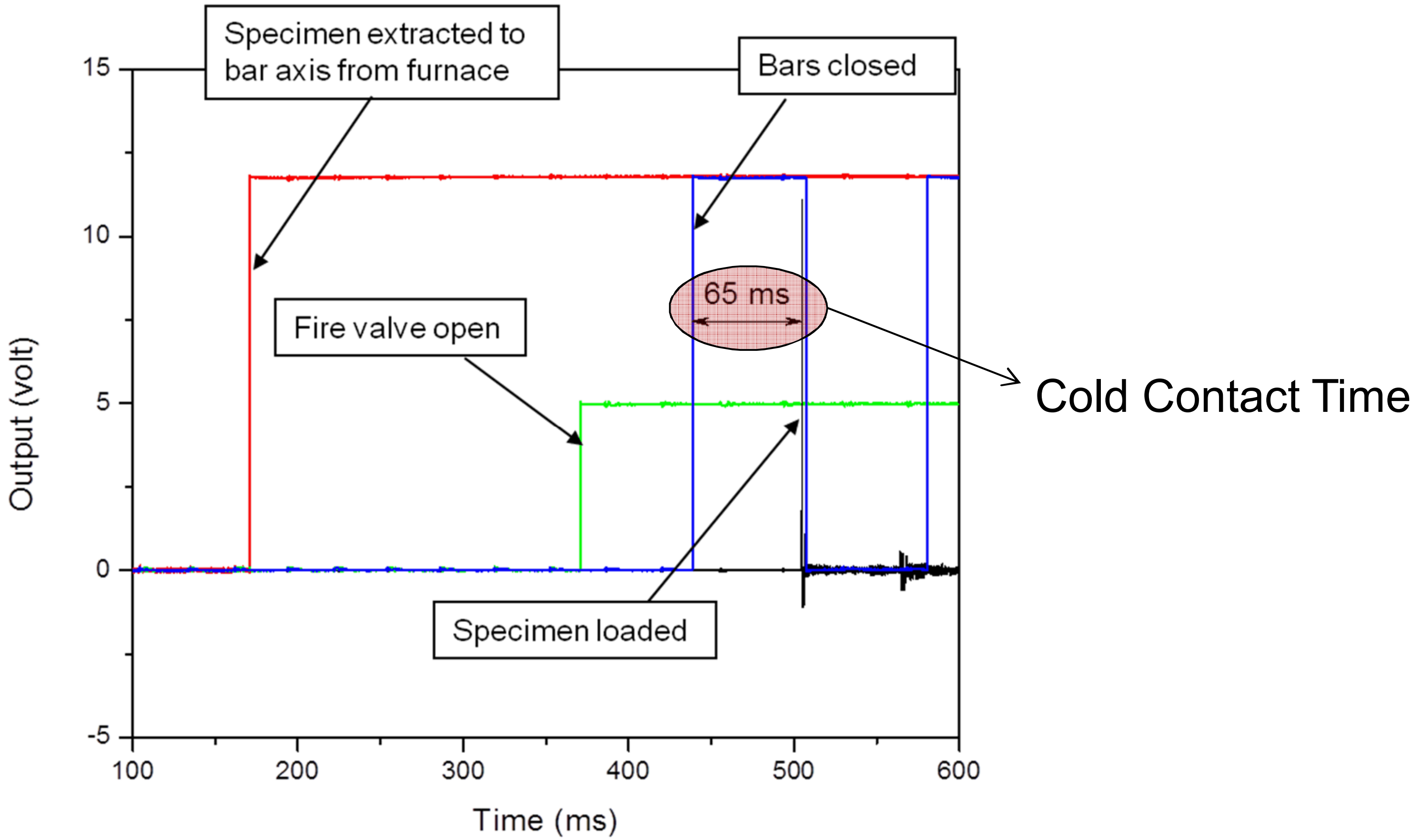


High-Rate/High-Temperature Testing of 304L Stainless Steel



The video has been edited to shorten playing time.

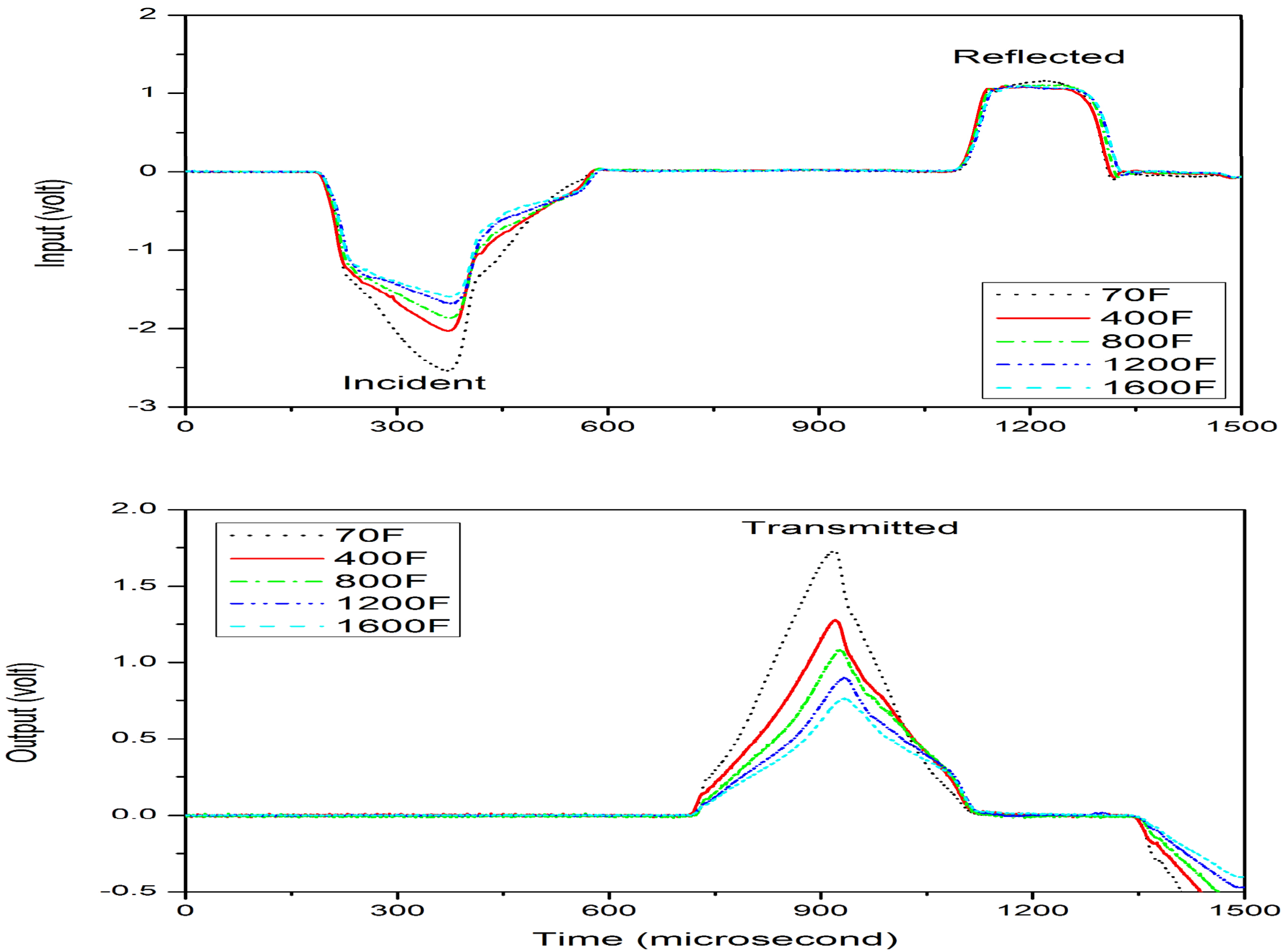
Cold Contact Time



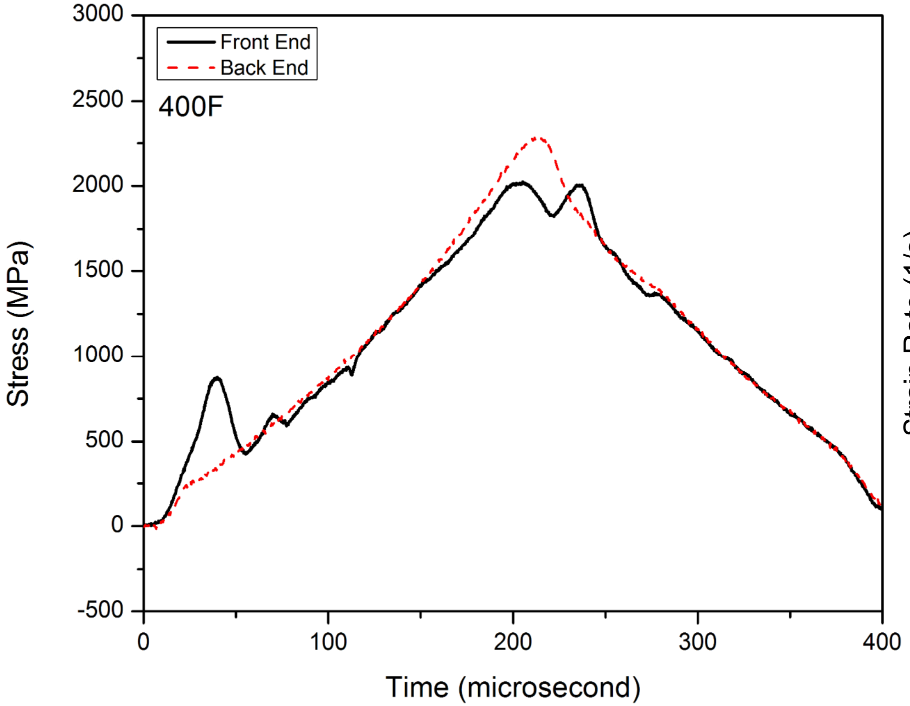
Cold contact time could be even shorter after more precise control of valve delay.

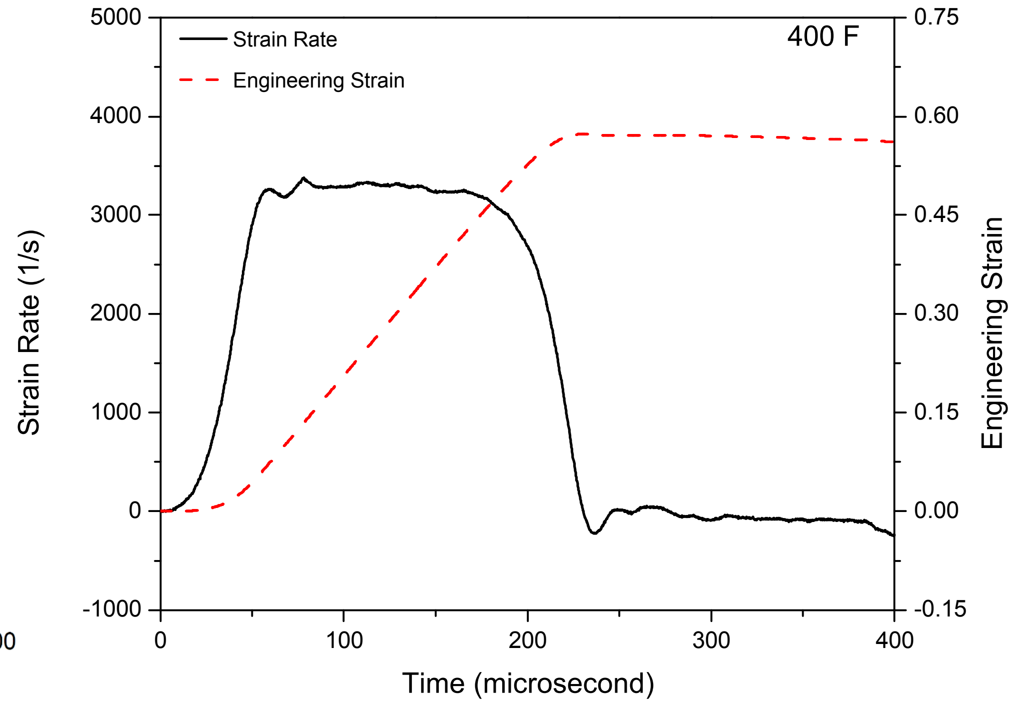
Pressure Bar Strain Gage Outputs with Proper Pulse Shaping Techniques

Sandia National Laboratories

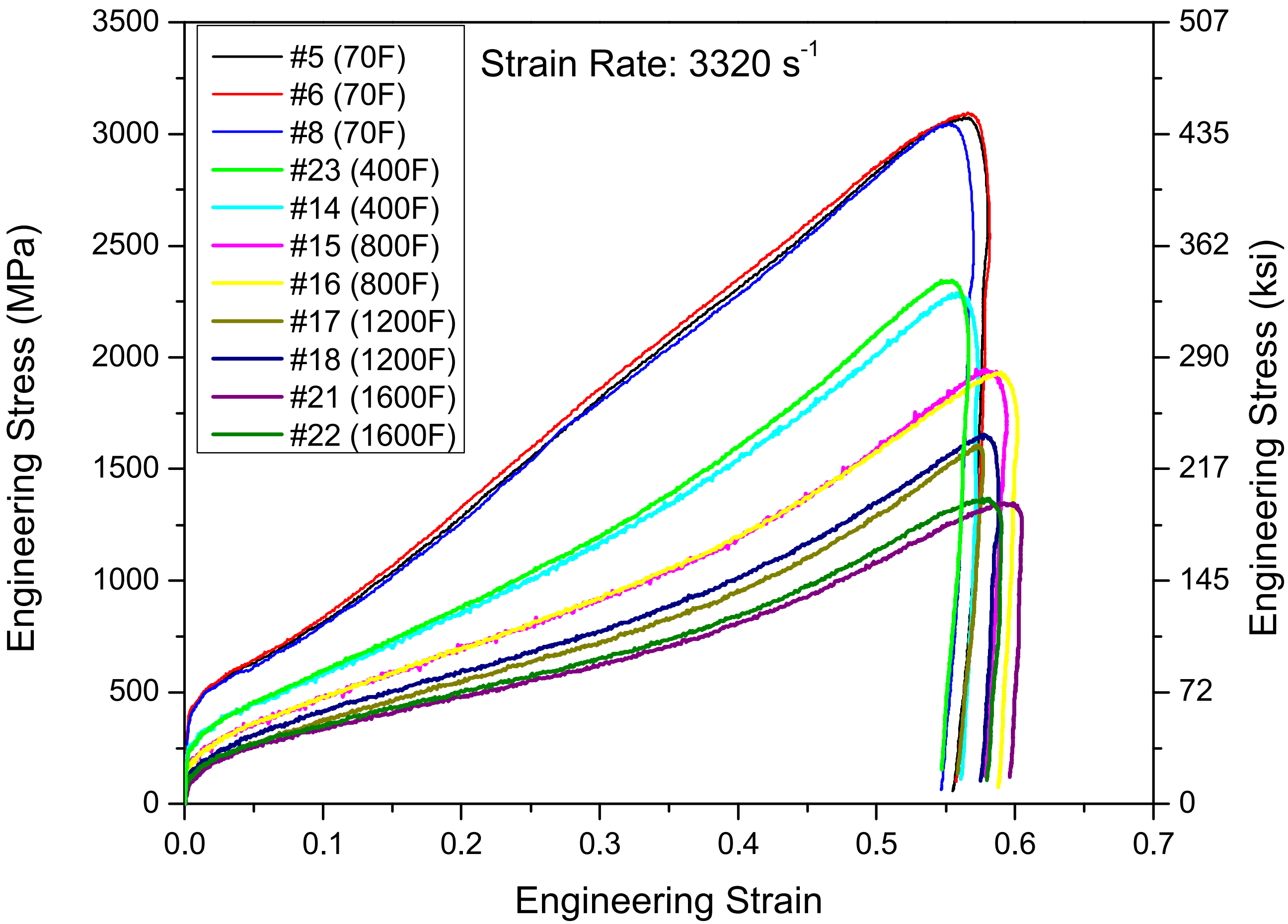


Stress Equilibrium and Constant Strain Rate

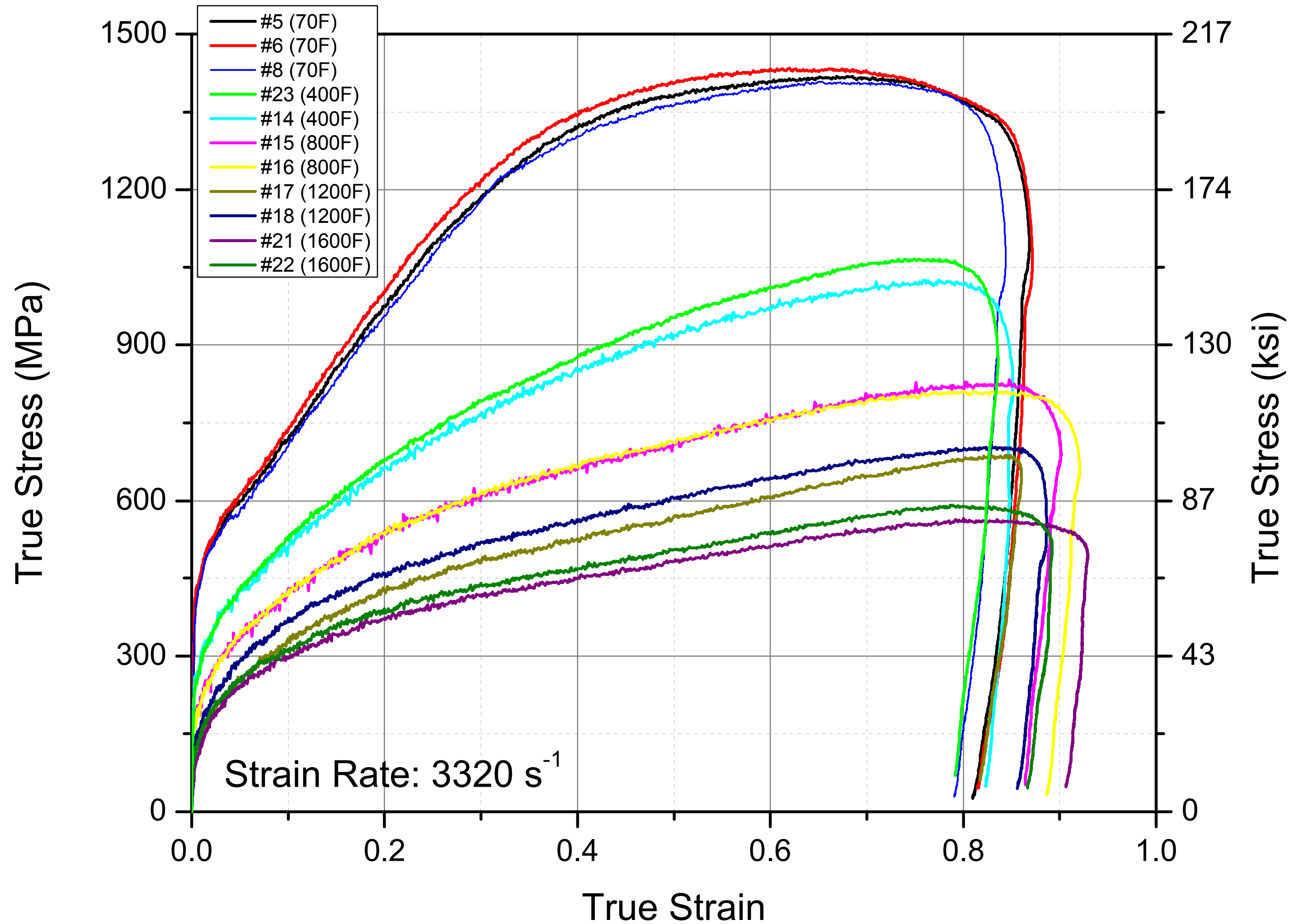




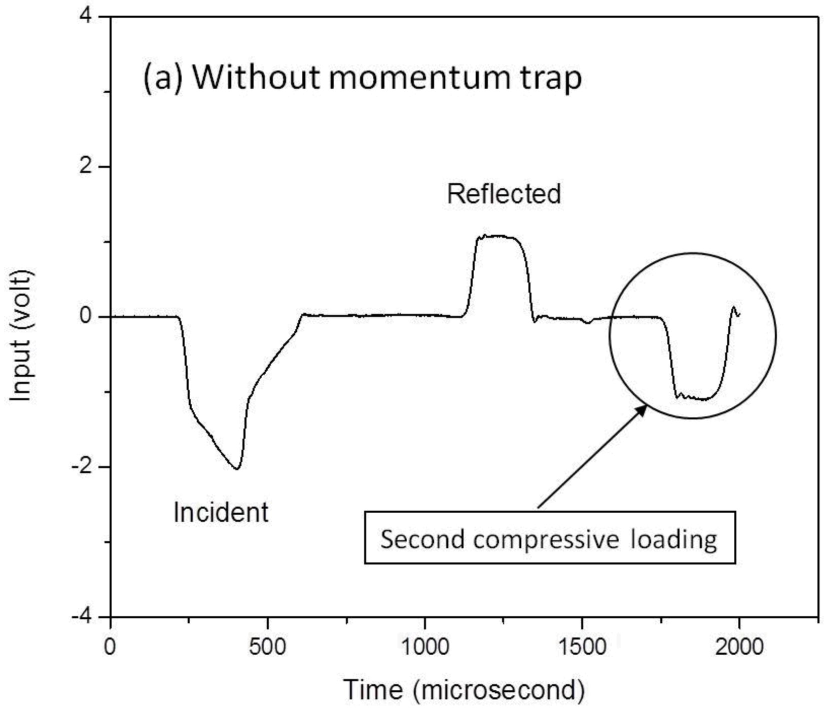
Dynamic Stress-Strain Curves

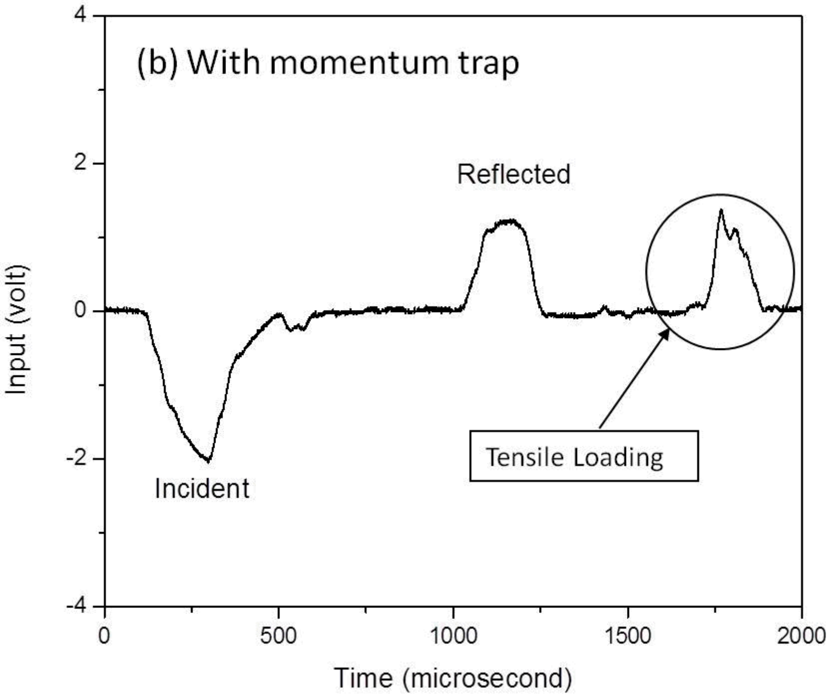


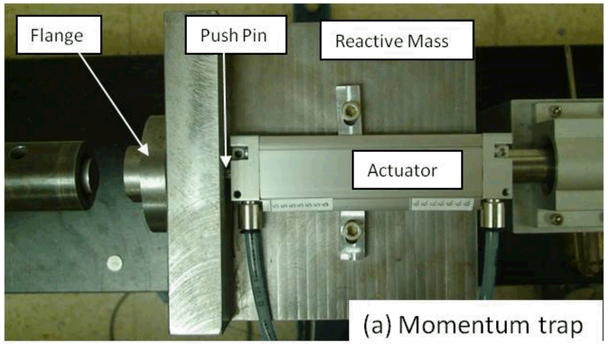
Dynamic Stress-Strain Curves

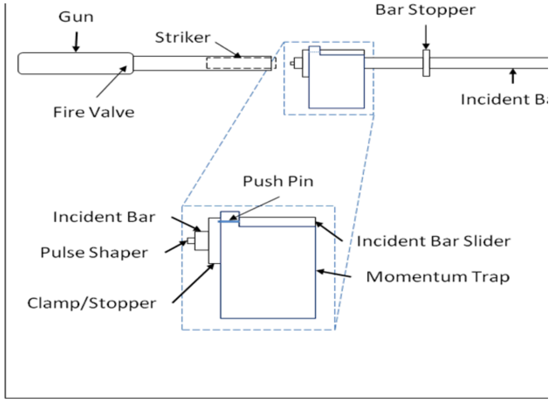


Momentum Trap for Single Loading

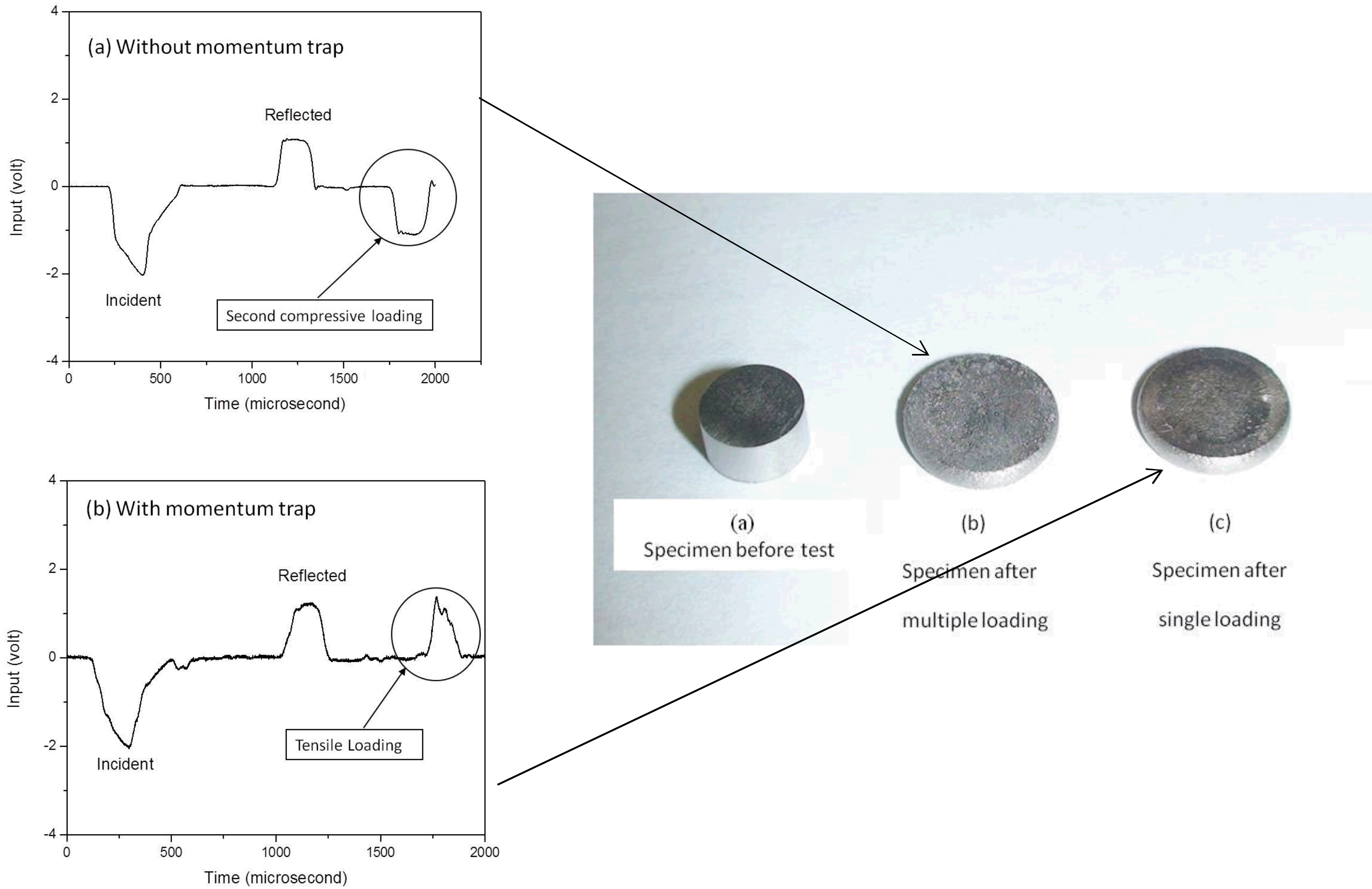




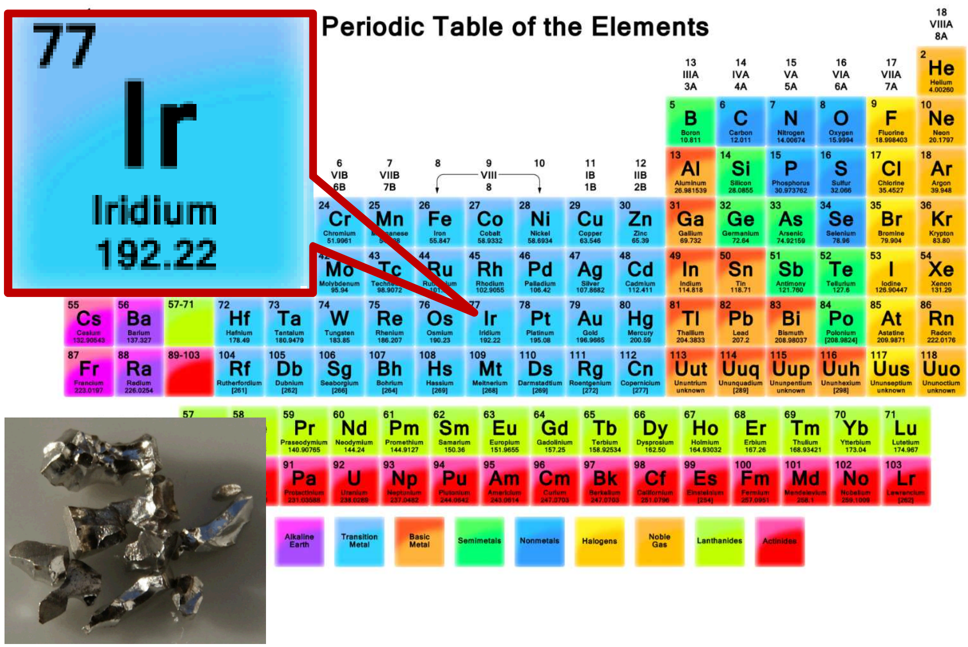




Specimens Before and After Tests



High-Temperature Split Hopkinson (Kolsky) Tension Bar Experiments on Iridium Alloy for Failure Analysis



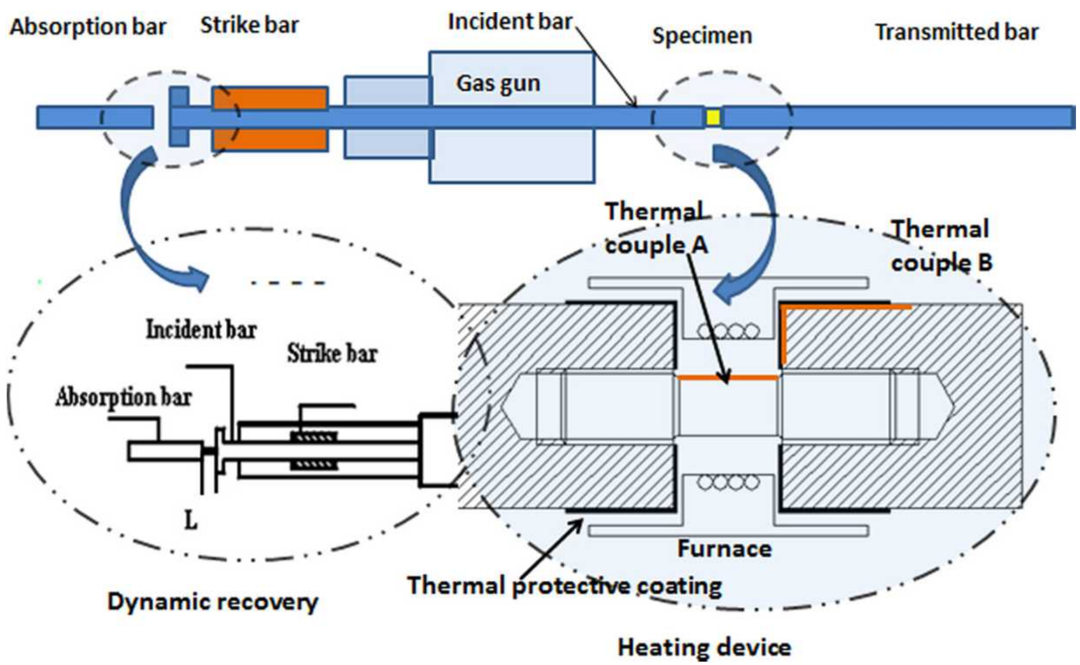
DOP-26 Iridium Alloy (developed by ORNL)

- *By weight:*
  - *0.3% tungsten to enhance weldability*
  - *60-ppm (parts per million) thorium to increase ductility*
  - *50-ppm aluminum*
- *Unique properties*
  - *High-melting point*
  - *Good high-temperature strength*
  - *Good oxidation resistance*
  - *Compatibility with the fuel and graphitic heat-source components*
  - *High impact ductility at high temperatures*

Current high-temperature Hopkinson compression techniques are not applicable to tensile tests

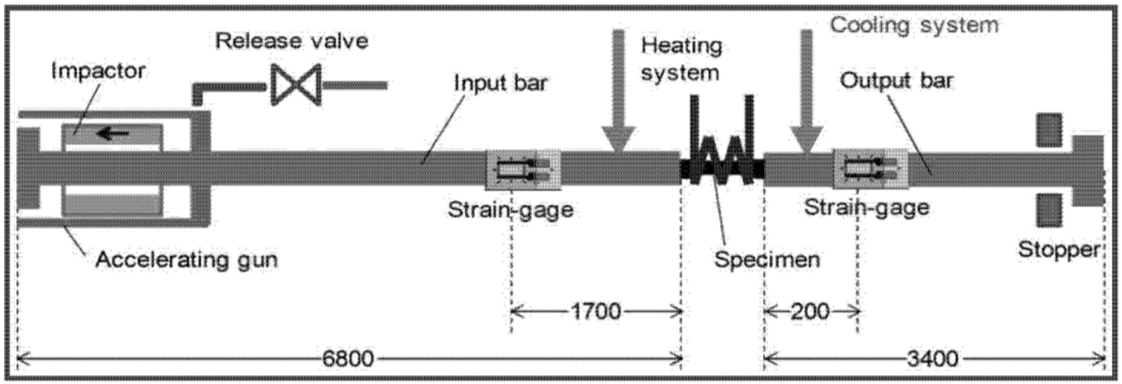
High-Temperature Kolsky Tensile Bar Tests

Su et al. (2013)



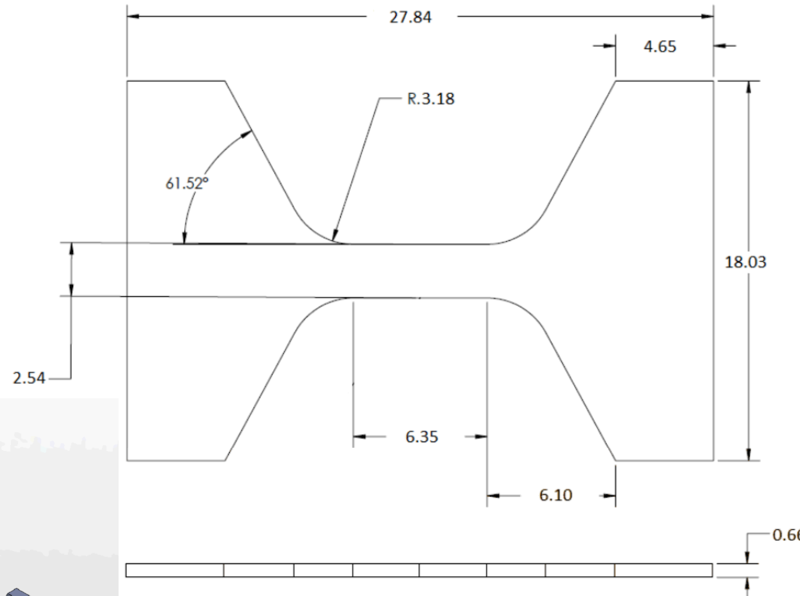
T < 600C

Scapin et al. (2014)

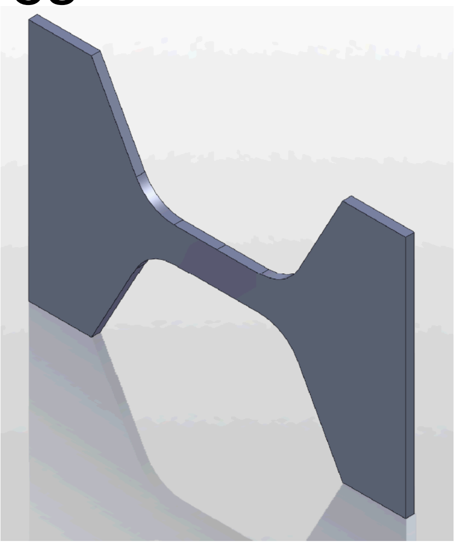


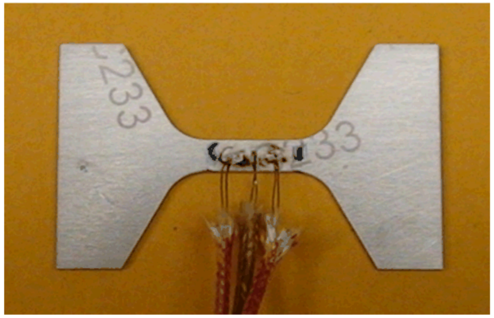
Challenges in High-Temperature Kolsky Tensile Bar Tests of Iridium

- DOP-26 iridium alloy: only 660-um-thick thin sheet
  - Special grips/fixtures
  - Specimen geometry design
  - Small cross-sectional area
    - Small transmitted force



- Ultra-high temperatures
  - 750 and 1030C
  - Hot specimen/cool ba
  - Thermal expansion
    - Possible buckling





High-Temperature Kolsky Tensile Bar Tests

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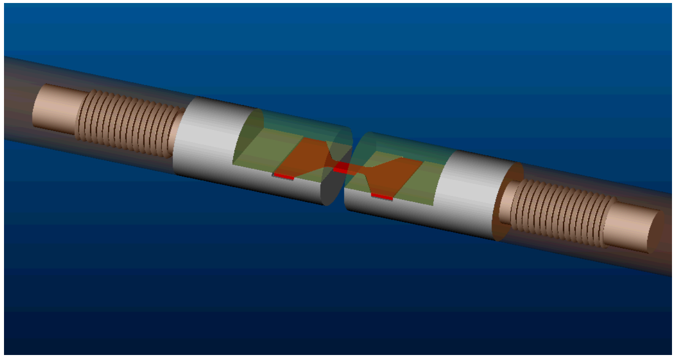

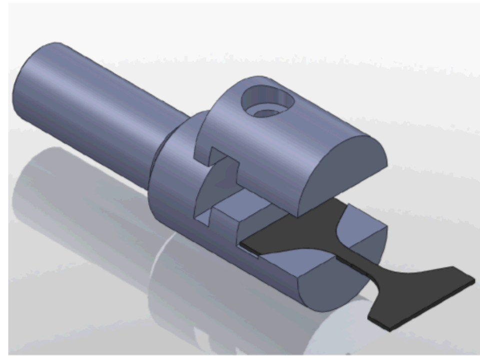

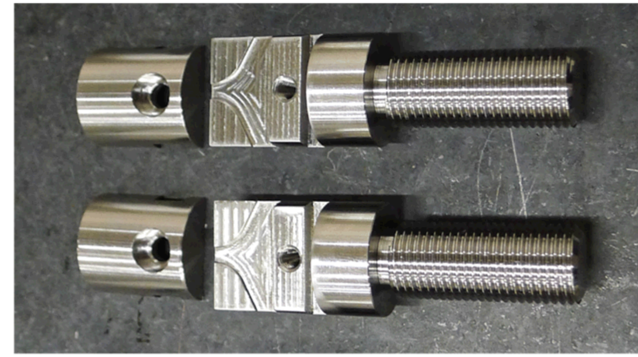

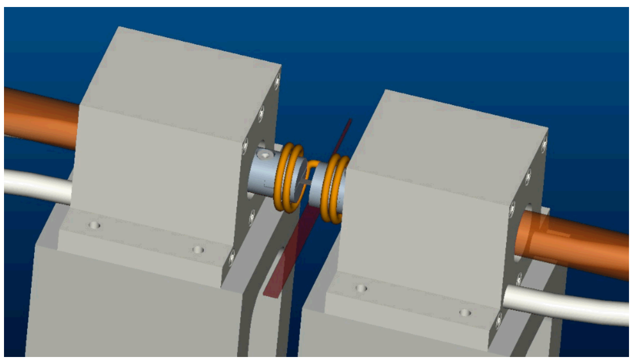

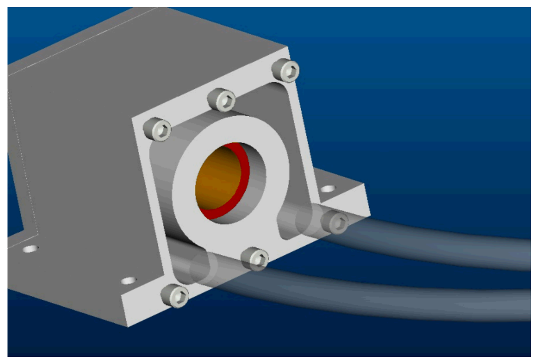

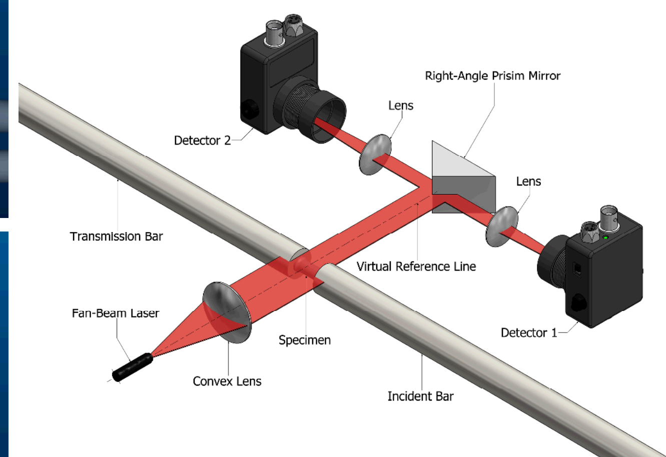

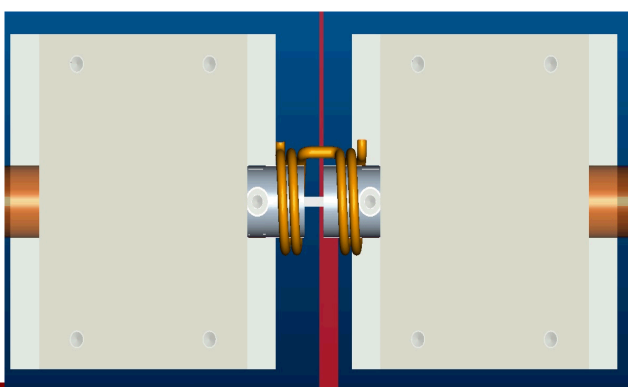

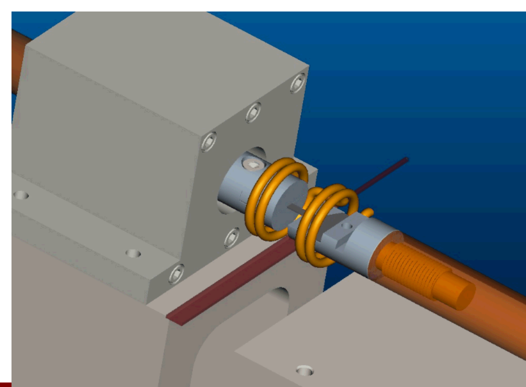

Stress and Strain Measurements

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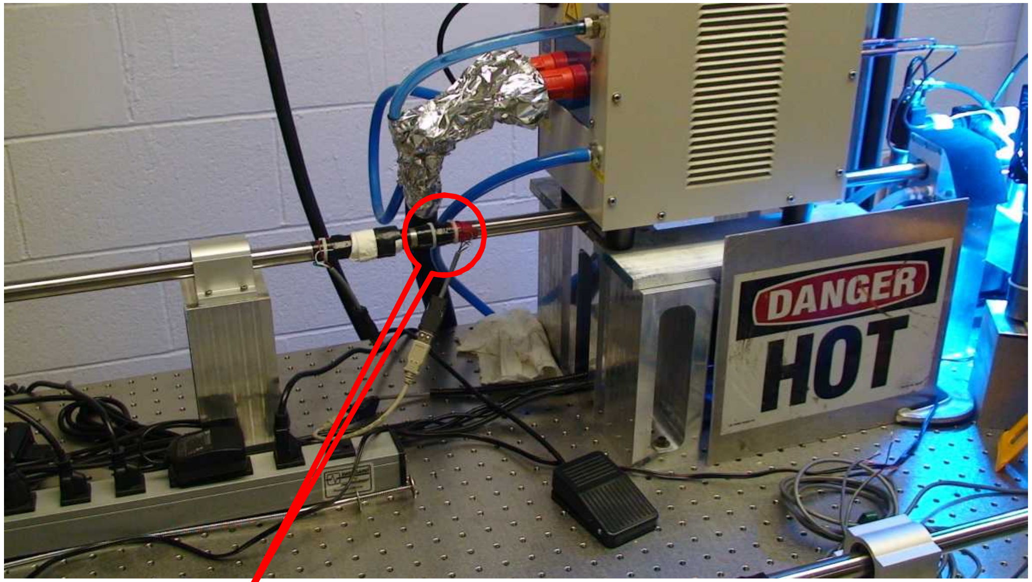
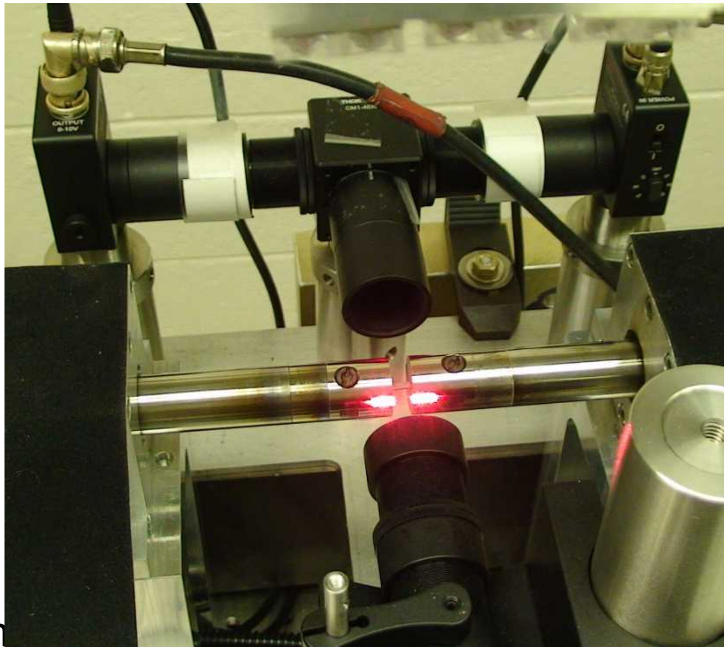
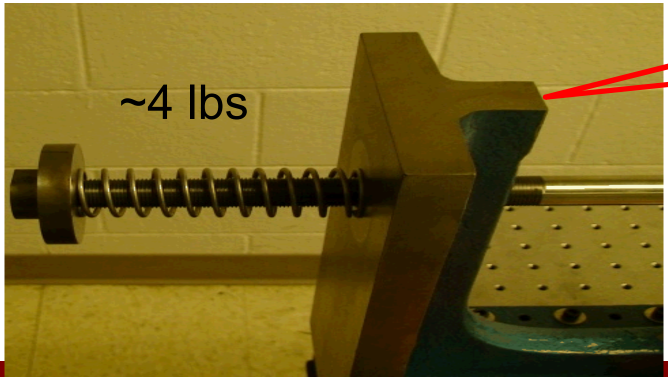
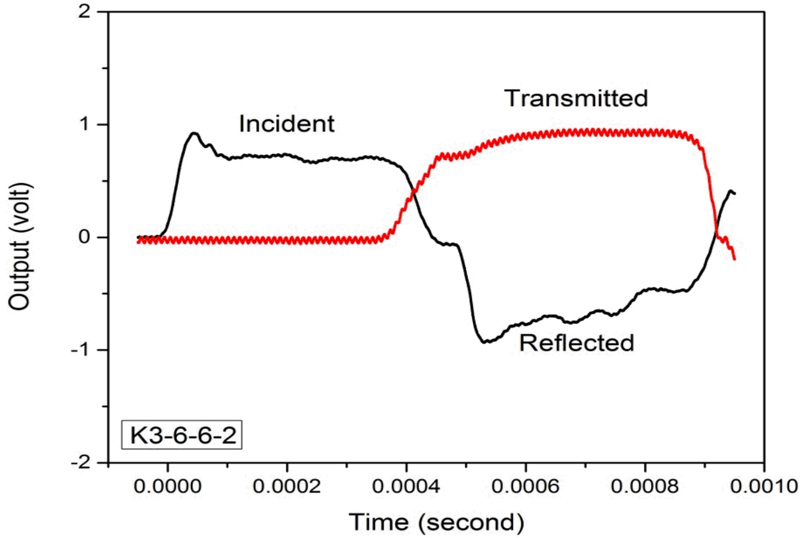


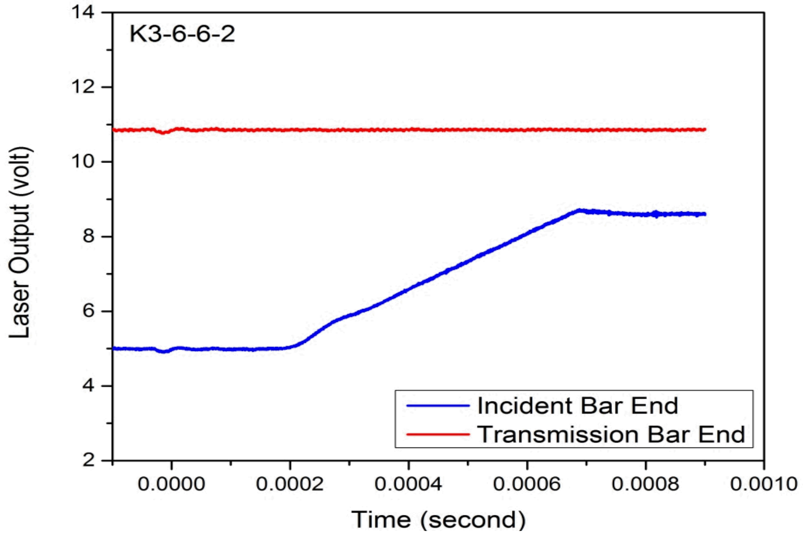


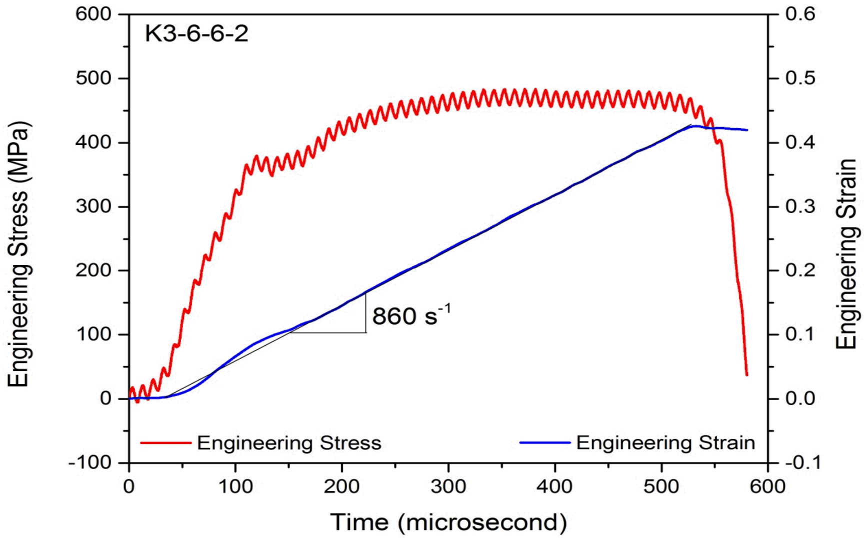
Semiconductor strain gages – specimen stress measurem
(GF: 139 vs. 2 for regular foil strain gage)

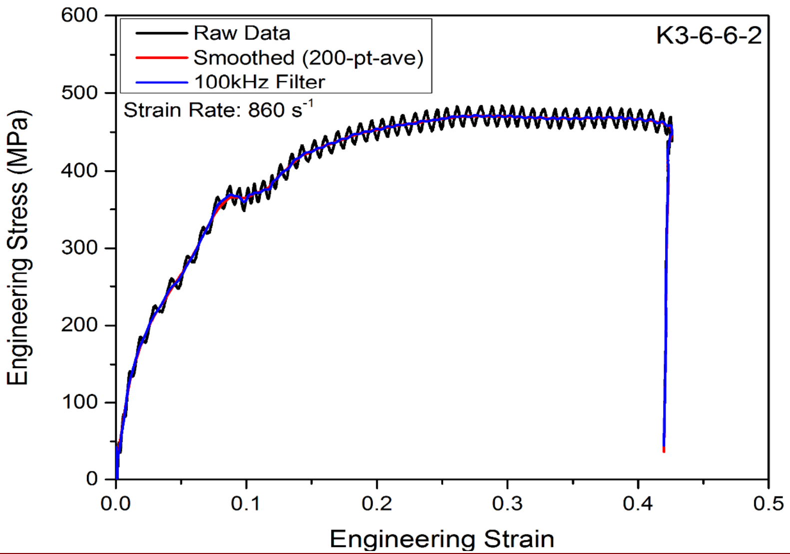


Typical Dynamic High-Temperature Tensile Test

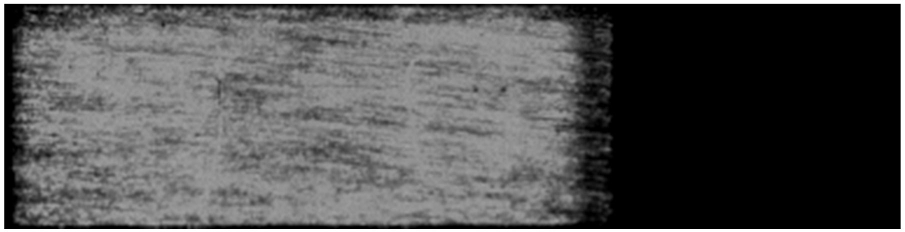


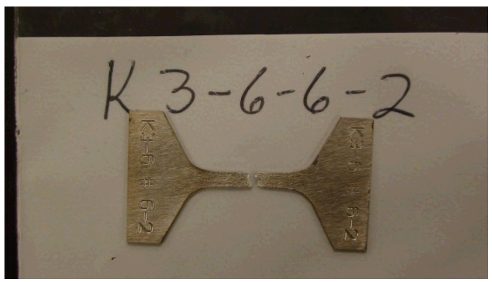






Specimen During and After Dynamic High-Temperature Test

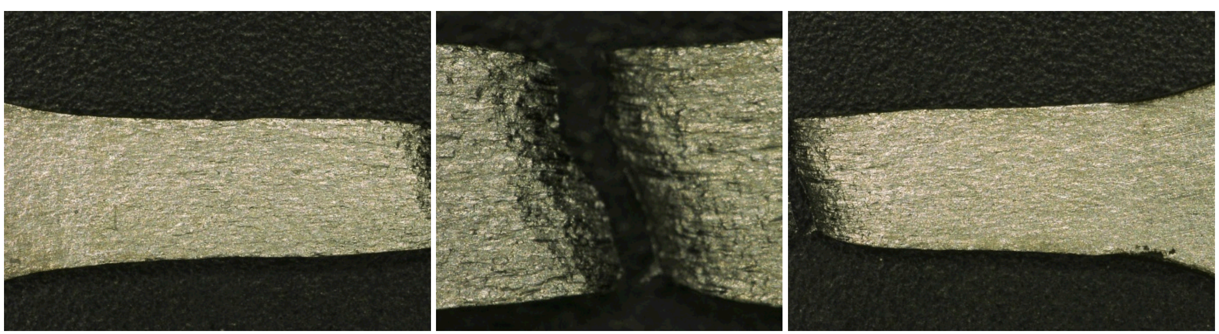




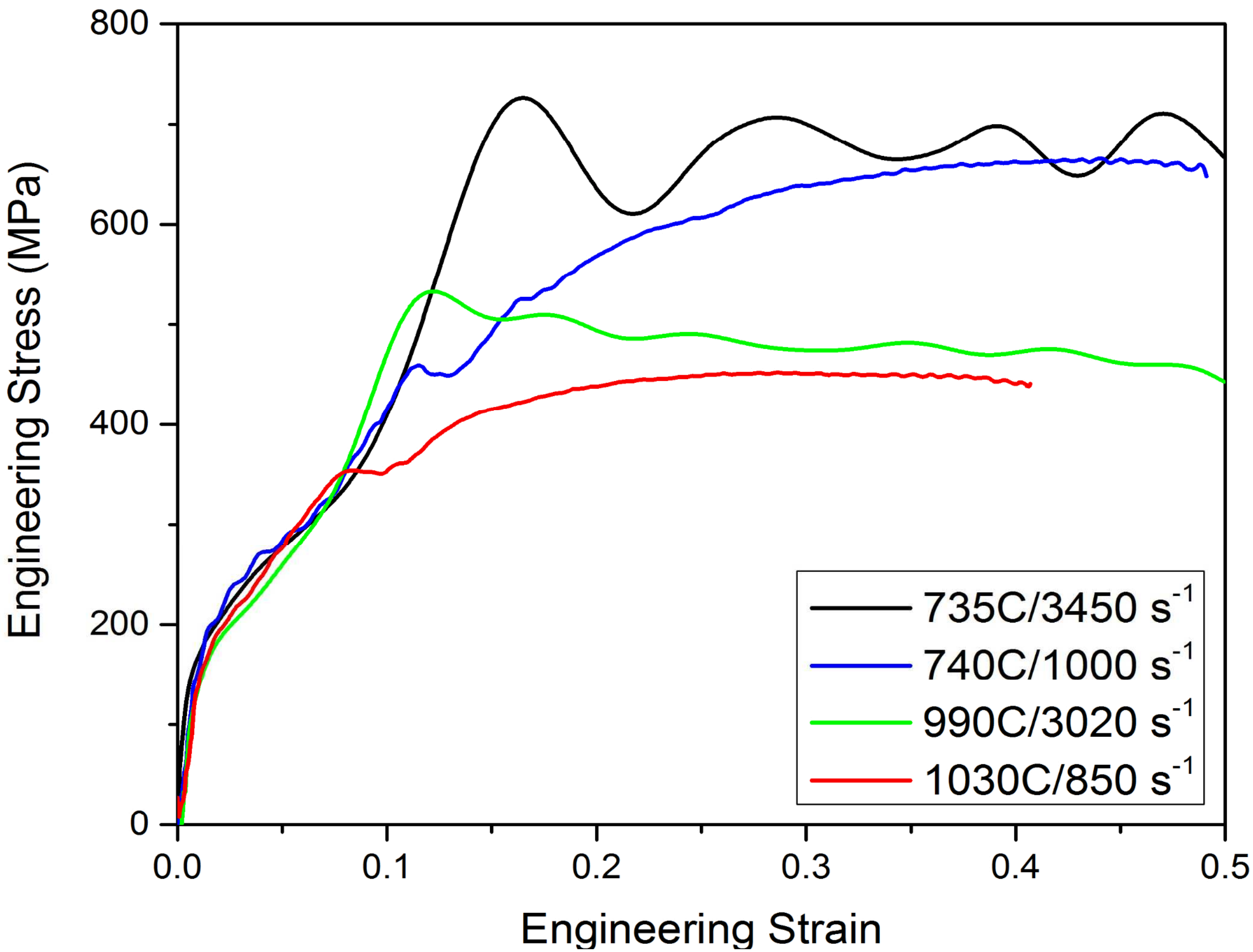
		K3-6-6-2		
Initial Measurements		After Measurements		
(in.)	(mm)		(mm)	
0.03590	0.9119	*	1.3406	
0.03495	0.8877		Break	
0.03495	0.8877	*	1.3467	
0.03495	0.8877		1.3606	
0.03485	0.8852		1.2579	
0.03505	0.8903			

** One or both indentations were difficult to detec
Measurement value is suspect

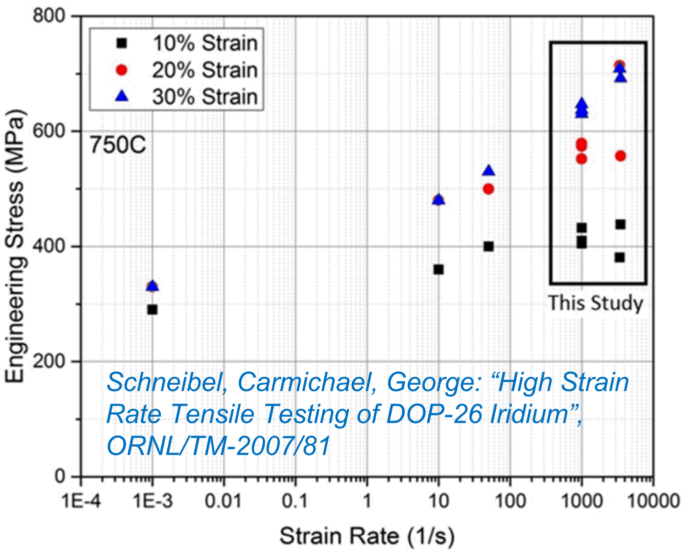
Average				
0.03511	0.89175			
	3.5725		5.3058	0.485

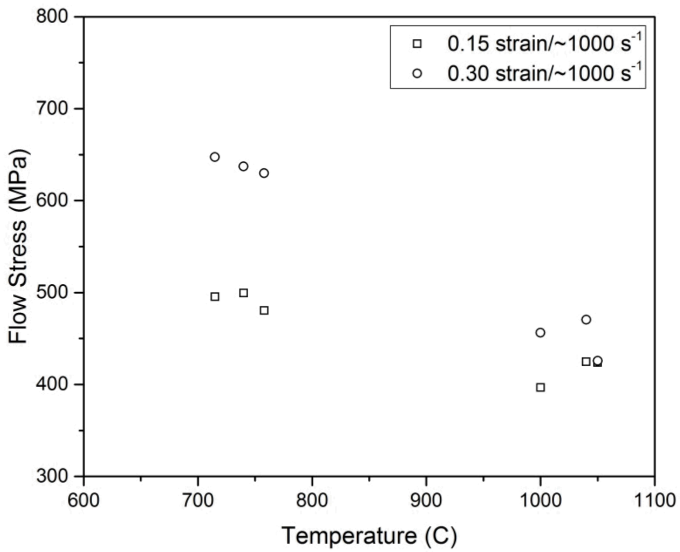


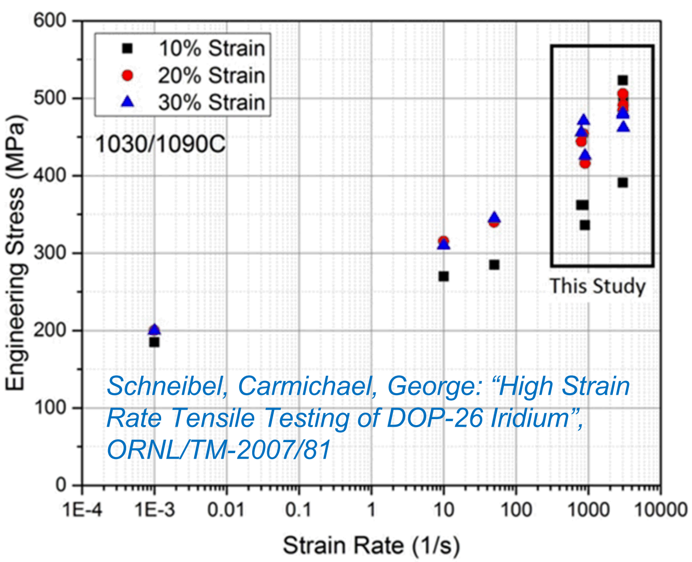
Engineering Tensile Stress-Strain Curves at Different Strain Rates and Temperatures

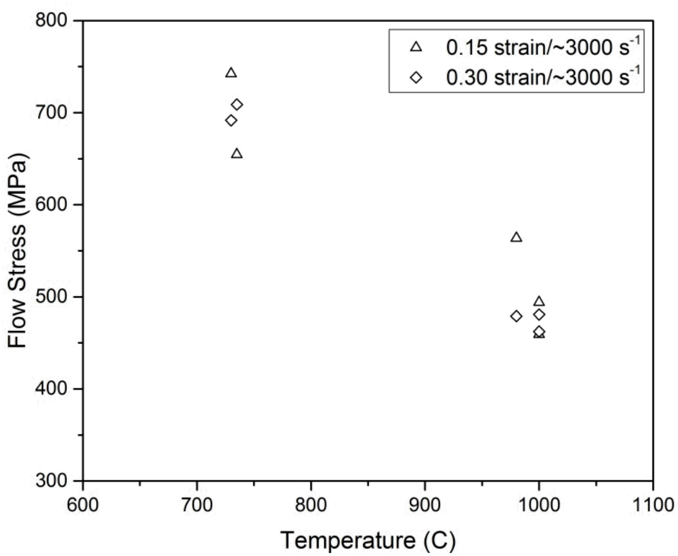


Strain-Rate and Temperature Effects









Summary

- High-temperature high-rate experiments with Kolsky bars are important but challenging
  - Similar challenges but different solutions for compressive and tensile tests
  - Current experimental techniques developed at Sandia are applicable up to 1030C
  - Examples:
    - 304L stainless steel for recrystallization
    - DOP-26 iridium alloy for safety analysis

- Here is just one example … we have been doing a lot of more fun stuff...

Experimental Impact Mechanics Lab

Sandia National Laboratories

- **"Who we are?"**
  - We are mechanical engineers/experimentalists to solve real engineering problems for a variety of applications

- **"What do we do?"**
  - We run experiments/mechanical testing but we are not just simply data factory
  - We design experiments, innovate experimental and diagnostic techniques, and advance engineering sciences
  - ***We are motivated to collaborate with universities on fundamental research and applications***

- **"What skills do we expect (for recruitment)?"**
  - Critical thinking (crazy ideas are always welcome!)
  - Problem solving
  - Challenge loving
  - Team work

EIML POC (Lead/Principal Investigator)

Sandia National Laboratories

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