

## **SANDIA REPORT**

SAND2014-15442

Unlimited Release

JUNE 2014

# **Dynamic High-Temperature Characterization of an Iridium Alloy in Compression at High Strain Rates**

Bo Song, Kevin Nelson, Ronald Lipinski, John Bignell  
Sandia National Laboratories

G. B. Ulrich, E. P. George  
Oak Ridge National Laboratory

Prepared by  
Sandia National Laboratories  
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.



**Sandia National Laboratories**

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

**NOTICE:** This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from

U.S. Department of Energy  
Office of Scientific and Technical Information  
P.O. Box 62  
Oak Ridge, TN 37831

Telephone: (865) 576-8401  
Facsimile: (865) 576-5728  
E-Mail: [reports@adonis.osti.gov](mailto:reports@adonis.osti.gov)  
Online ordering: <http://www.osti.gov/bridge>

Available to the public from

U.S. Department of Commerce  
National Technical Information Service  
5285 Port Royal Rd.  
Springfield, VA 22161

Telephone: (800) 553-6847  
Facsimile: (703) 605-6900  
E-Mail: [orders@ntis.fedworld.gov](mailto:orders@ntis.fedworld.gov)  
Online order: <http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online>



# Dynamic High-Temperature Characterization of an Iridium Alloy in Compression at High Strain Rates

Bo Song<sup>1</sup>, Kevin Nelson<sup>2</sup>, Ronald Lipinski<sup>3</sup>, John Bignell<sup>4</sup>

<sup>1</sup> Experimental Environment Simulation Department; <sup>3</sup> Advanced Nuclear Fuel Cycle  
Technology Department; <sup>4</sup> Structural and Thermal Analysis Department  
Sandia National Laboratories  
P.O. Box 5800, Albuquerque, New Mexico 87185

<sup>2</sup> Mechanics of Materials Department  
Sandia National Laboratories  
P.O. Box 0969, Livermore, California 94550

G. B. Ulrich, E. P. George

Radioisotope Power Systems Program  
Oak Ridge National Laboratory  
Oak Ridge, Tennessee 37831-6079

## Abstract

Iridium alloys have superior strength and ductility at elevated temperatures, making them useful as structural materials for certain high-temperature applications. However, experimental data on their high-temperature high-strain-rate performance are needed for understanding high-speed impacts in severe elevated-temperature environments. Kolsky bars (also called split Hopkinson bars) have been extensively employed for high-strain-rate characterization of materials at room temperature, but it has been challenging to adapt them for the measurement of dynamic properties at high temperatures. Current high-temperature Kolsky compression bar techniques are not capable of obtaining satisfactory high-temperature high-strain-rate stress-strain response of thin iridium specimens investigated in this study. We analyzed the difficulties encountered in high-temperature Kolsky compression bar testing of thin iridium alloy specimens. Appropriate modifications were made to the current high-temperature Kolsky compression bar technique to obtain reliable compressive stress-strain response of an iridium alloy at high strain rates (300 – 10000 s<sup>-1</sup>) and temperatures (750°C and 1030°C). Uncertainties in such high-temperature high-strain-rate experiments on thin iridium specimens were also analyzed. The compressive stress-strain response of the iridium alloy showed significant sensitivity to strain rate and temperature.

## **ACKNOWLEDGMENTS**

This work was sponsored by the United States Department of Energy (DOE) Office of Space and Defense Power Systems (NE-75). The authors gratefully acknowledge the support and guidance of Ryan D. Bechtel of the U.S. Department of Energy.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Oak Ridge National Laboratory is a multi-program research laboratory managed by UT-Battelle, LLC, for the U.S. DOE under contract DE-AC05-00OR22725.

## CONTENTS

|                                                                                                       |    |
|-------------------------------------------------------------------------------------------------------|----|
| 1. Introduction.....                                                                                  | 9  |
| 2. Modified Automated High-temperature Kolsky bar for Thin Iridium Specimen<br>Characterization ..... | 13 |
| 2.1. The Automated High-temperature Kolsky Bar at SNL .....                                           | 13 |
| 2.2. Issues in High-Temperature Kolsky Testing of Iridium .....                                       | 15 |
| 2.3. High-Temperature Kolsky Bar Design for Iridium Alloy Testing .....                               | 21 |
| 3. Dynamic High-temperature Experiments .....                                                         | 23 |
| 3.1. Iridium Alloy Specimen Preparation .....                                                         | 23 |
| 3.2. Dynamic High-temperature Experiments .....                                                       | 23 |
| 3.3. Uncertainty Analysis.....                                                                        | 28 |
| 3.4. Experimental Results .....                                                                       | 30 |
| 4. Conclusions.....                                                                                   | 47 |
| 5. References.....                                                                                    | 49 |
| APPENDIX A: Summary of Dynamic Testing Conditions of Individual Samples .....                         | 51 |
| Distribution .....                                                                                    | 53 |

## FIGURES

|                                                                                                                             |    |
|-----------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1. Conventional Kolsky compression bar system.....                                                                   | 10 |
| Figure 2. Temperature effect on Young's modulus of Inconel 718.....                                                         | 11 |
| Figure 3. Schematic of automated high-temperature Kolsky compression bar system. ....                                       | 13 |
| Figure 4. Operational steps for the high-temperature Kolsky compression bar testing.....                                    | 14 |
| Figure 5. Temperature change of an iridium alloy specimen after contact with the pressure bars.<br>.....                    | 16 |
| Figure 6. Comparison of the cool-down histories of iridium specimens sandwiched between<br>different platen materials ..... | 17 |
| Figure 7. Illustration of specimen fixture configuration. ....                                                              | 18 |
| Figure 8. Thermocouple locations. ....                                                                                      | 19 |
| Figure 9. Temperature histories at different locations. ....                                                                | 19 |
| Figure 10. Temperature histories at different locations within the time window of dynamic<br>testing. ....                  | 20 |
| Figure 11. Lubrication performance of SEG graphite at high temperatures.....                                                | 21 |
| Figure 12. High-temperature Kolsky bar set-up for iridium testing. ....                                                     | 22 |
| Figure 13. Different stages in the installation of an iridium specimen. ....                                                | 22 |
| Figure 14. Typical incident, reflected, and transmitted signals. ....                                                       | 24 |
| Figure 15. Dynamic stress equilibrium. ....                                                                                 | 25 |
| Figure 16. Strain-rate and strain histories. ....                                                                           | 25 |
| Figure 17. Temperature history.....                                                                                         | 26 |
| Figure 18. Representative engineering stress-strain curve at 1000/s, 750°C.....                                             | 27 |
| Figure 19. Representative true stress-strain curve at 1000/s, 750°C. ....                                                   | 27 |

|                                                                          |    |
|--------------------------------------------------------------------------|----|
| Figure 20. Young's modulus of alumina at high temperatures.....          | 30 |
| Figure 21. Compressive stress-strain curves at 420/s, 750°C.....         | 32 |
| Figure 22. Compressive stress-strain curves at 1000/s, 750°C.....        | 33 |
| Figure 23. Compressive stress-strain curves at 3350/s, 750°C.....        | 34 |
| Figure 24. Compressive stress-strain curves at 11550/s, 750°C.....       | 35 |
| Figure 25. Compressive stress-strain curves at 340/s, 1030°C.....        | 36 |
| Figure 26. Compressive stress-strain curves at 1080/s, 1030°C.....       | 37 |
| Figure 27. Compressive stress-strain curves at 3450/s, 1030°C.....       | 38 |
| Figure 28. Compressive stress-strain curves at 10300/s, 1030°C.....      | 39 |
| Figure 29. Compressive stress-strain curves at 750°C. ....               | 40 |
| Figure 30. Compressive stress-strain curves at 1030°C. ....              | 41 |
| Figure 31. Temperature and strain rate effects .....                     | 42 |
| Figure 32. Strain rate effect at 750°C .....                             | 43 |
| Figure 33. Strain rate effect at 1030°C .....                            | 43 |
| Figure 34. Strain-rate and temperature effects at different strains..... | 45 |

## TABLES

|                                                                  |    |
|------------------------------------------------------------------|----|
| Table 1. Material properties used for thermal analysis.....      | 16 |
| Table 2. Striker dimensions for different strain rate tests..... | 23 |
| Table 3. Dynamic testing conditions of samples .....             | 51 |

## NOMENCLATURE

|      |                               |
|------|-------------------------------|
| CCT  | Cold contact time             |
| SEG  | Super enhanced graphite       |
| SHB  | Split Hopkinson bar           |
| SHPB | Split Hopkinson pressure bar  |
| SNL  | Sandia National Laboratories  |
| ORNL | Oak Ridge National Laboratory |

*This page intentionally left blank.*

# 1. INTRODUCTION

Iridium alloys have been utilized in certain high-temperature applications, due to their unique combinations of high melting temperature, high-temperature strength and ductility, and excellent oxidation and corrosion resistance [1]. When iridium alloys are used as cladding material for containment of heat sources, safety is paramount. Typically these materials must have excellent impact resistance at high temperatures. Experimental data are required to assess their performance at the pertinent high strain rates and temperatures.

The mechanical properties of iridium alloys have been investigated before at various strain rates [2-4]. However, the strain rates in the literature were either not sufficiently high for all potential applications, or the stress-strain curves of the iridium alloys could not be obtained due to instrument limitations. It has been especially challenging to dynamically characterize materials at high temperatures, even though Kolsky bar (also called split Hopkinson bar, SHB) testing has been extensively employed for high strain-rate characterization of materials at room temperature [5].

Figure 1 shows a conventional Kolsky compression bar (or split Hopkinson pressure bar, SHPB) system for high-rate material characterization at room temperature [5]. This system consists of a striker and two compression bars (an incident bar and a transmission bar). The striker is launched by an air gun through sudden release of compressed air. The specimen is placed between the incident and transmission bars, as shown in Fig. 1. When the striker impacts the end of the incident bar, compressive stress waves are generated and propagate in both the striker and the incident bar. The stress wave generated in the incident bar is called an “incident wave”, which propagates toward the specimen along the incident bar. When the incident wave arrives at the incident bar/specimen interface, part of it is reflected back into the incident bar as a “reflected wave” and the rest transmits into the transmission bar through the specimen as a “transmitted wave”, due to the mismatched mechanical impedance between the compression bars and the specimen. The incident wave and reflected wave are measured with the strain gages on the incident bar while the transmitted wave is measured with the strain gages on the transmission bar (Fig. 1). Both incident and transmission bars are slender to ensure nearly one-dimensional stress wave propagation. According to one-dimensional stress wave theory, the strain rate, strain, and stress in the specimen are calculated as

$$\dot{\varepsilon} = \frac{v_1 - v_2}{L_s} = \frac{C_B}{L_s} (\varepsilon_i - \varepsilon_r - \varepsilon_t) \quad (1)$$

$$\varepsilon = \int_0^t \dot{\varepsilon} dt = \frac{C_B}{L_s} \int_0^t (\varepsilon_i - \varepsilon_r - \varepsilon_t) dt \quad (2)$$

$$\sigma_1 = \frac{A_B}{A_s} \cdot E_B (\varepsilon_i + \varepsilon_r) \quad (3)$$

$$\sigma_2 = \frac{A_B}{A_s} \cdot E_B \varepsilon_t \quad (4)$$

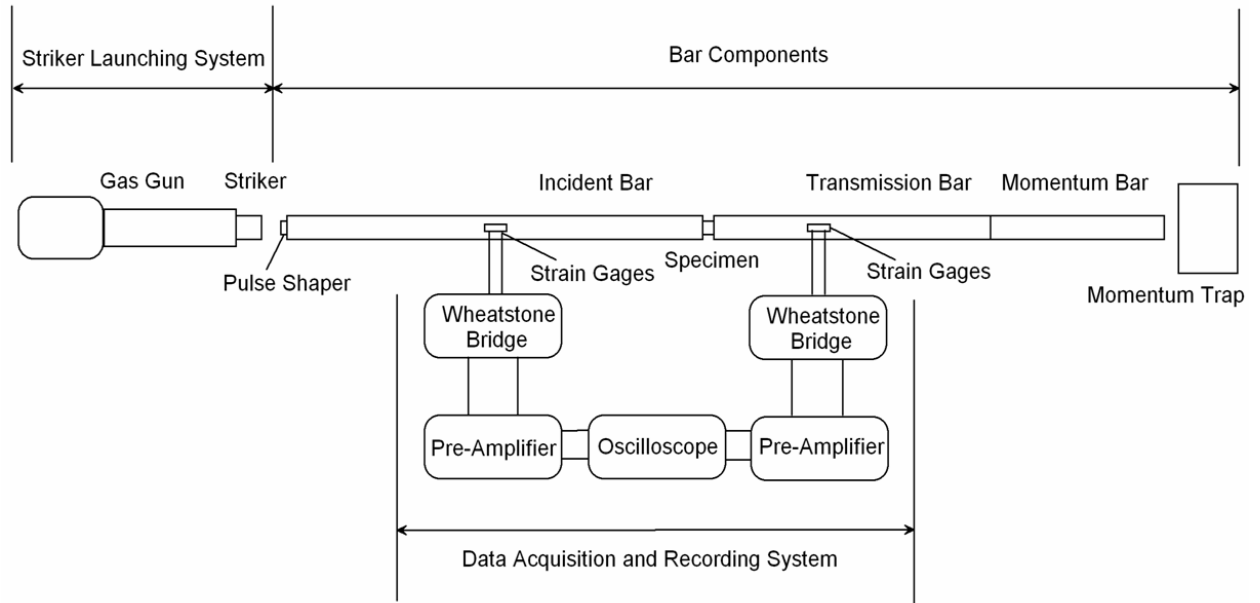
where the subscripts,  $i$ ,  $r$ , and  $t$ , represent the incident, reflected, and transmitted pulses, respectively;  $L_s$  is the original length of the specimen;  $A_B$  and  $A_s$  are the cross-sectional areas of the bars and the specimen, respectively;  $C_B$  and  $E_B$  are one-dimensional elastic longitudinal wave speed and Young's modulus of the bar material, respectively;  $\sigma_1$  and  $\sigma_2$  represent the stresses at the front and back ends of the specimen, respectively. When the specimen stress is equilibrated,

$$\sigma_1 = \sigma_2 \quad (5a)$$

or

$$\varepsilon_i + \varepsilon_r = \varepsilon_t \quad (5b)$$

the calculations of specimen strain rate, strain, and stress are then simplified as



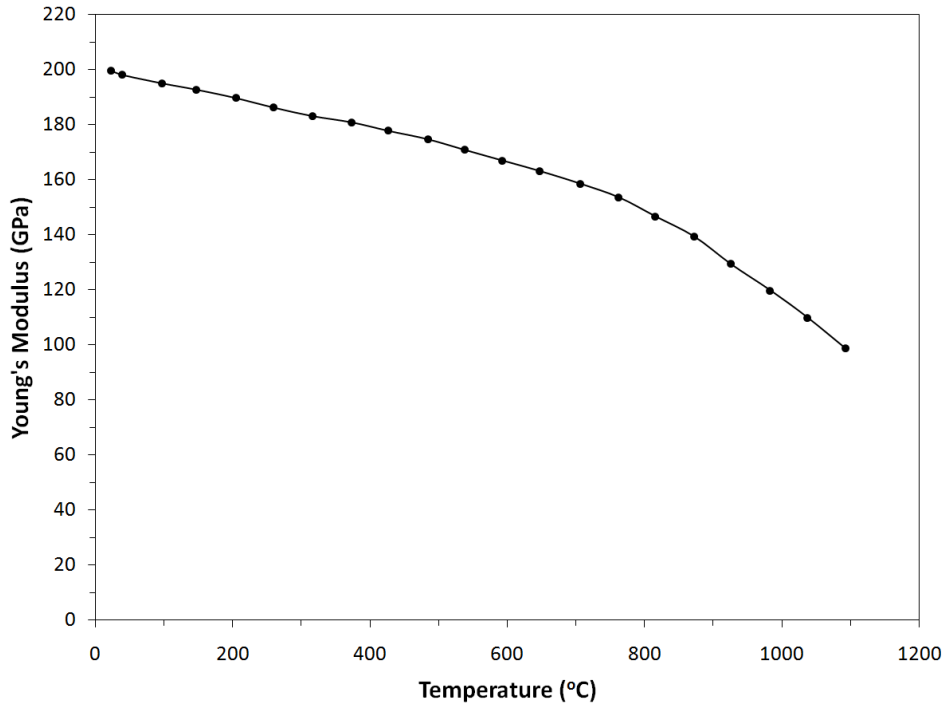
**Figure 1. Conventional Kolsky compression bar system.**

$$\dot{\varepsilon} = -2 \frac{C_B}{L_S} \varepsilon_r \quad (6)$$

$$\varepsilon = -2 \frac{C_B}{L_S} \int_0^t \varepsilon_r dt \quad (7)$$

$$\sigma = \frac{A_B}{A_s} \cdot E_B \cdot \varepsilon_t \quad (8)$$

The stress-strain curve can be obtained by eliminating the term of time in Eqs. (7) and (8).



**Figure 2. Temperature effect on Young's modulus of Inconel 718.**

In Kolsky bar experiments, the pressure bars serve as not only loading actuators but also mechanical sensors. The stress-strain calculation of the specimen material under investigation is typically based on the measurements of bar strains. In order to make such measurements reliable, the temperature must not change significantly so that the pressure bar mechanical parameters, e.g. Young's modulus, remain constant during the experiment. The Young's moduli of metals have been found to significantly decrease at high temperatures. Figure 2 shows an example of the temperature effect on the Young's modulus of Inconel 718 [6]. As shown in Fig. 2, the Young's modulus of Inconel 718 drops approximately by half at 1000°C in comparison to

that at room temperature. Even if the pressure bars are locally heated in the specimen testing section away from the strain-gage locations, significant temperature gradients are produced in both incident and transmission bars. Such temperature gradients generate mechanical impedance gradients, due to Young's modulus changes, in both incident and transmission bars, which modifies the stress wave propagation and influences the response of the strain gages on the bar surfaces. Thus, special care is needed to perform high-temperature Kolsky bar experiments.

As a remedy, some researchers have heated the specimen separately [7-10] in a furnace. Upon reaching the desired temperature, the hot specimen is sandwiched between the "cold" (room-temperature) pressure bars right before the dynamic load is applied. This introduces the concept of cold contact time (CCT), which is defined as the time during which the hot specimen is in contact with the cold pressure bars before it is dynamically loaded. It is highly desirable to make the CCT as short as possible to minimize both the temperature drop in the heated specimen and the gradient created in the room-temperature pressure bars from heat transfer between the "hot" specimen and the "cold" pressure bars. The CCT has been shortened in a few different ways. An electric screw driven system was developed by Frantz et al. [7] to bring the pressure bars into the furnace containing the preheated specimen and sandwiching the specimen between the pressure bars immediately before the striker was launched. Lennon and Ramesh [8] used an electropneumatic actuation system to quickly drive the incident and transmission bars into contact with the specimen being heated using an infrared spot heater. Kuokkala's group [9] has developed a fully automated high-temperature Kolsky compression bar system with precise control of the experimental procedure. Following Kuokkala's original design, Song et al. [10] developed a similar system for extended applications at SNL, which has been utilized to dynamically characterize the high-temperature response of 304L stainless steel as well as in a related recrystallization investigation. In the current research, this automated high-temperature Kolsky bar system was further modified to characterize an iridium alloy at high temperatures.

## 2. MODIFIED AUTOMATED HIGH-TEMPERATURE KOLSKY BAR FOR THIN IRIDIUM SPECIMEN CHARACTERIZATION

In this section, the current automated high-temperature Kolsky bar technique is described along with issues encountered during dynamic characterization of iridium alloys and the necessary modifications that were made.

### 2.1. The Automated High-temperature Kolsky Bar at SNL

Figure 3 shows a schematic of the automated high-temperature Kolsky bar system developed at SNL for dynamic high-temperature compression characterization of materials [10]. The pressure bars, which are made of C350 maraging steel, had a common diameter of 19.05 mm. The incident and transmission bars were 3657 mm and 2134 mm long, respectively. The striker material and length can be varied for mechanical testing at different strain rates. In comparison to the conventional Kolsky bar system shown in Fig. 1, the automated high-temperature Kolsky bar system utilized an electrical furnace located behind the specimen section, several pneumatic sliders, and a specially designed specimen holder. The specimen holder was attached to a pneumatic slider to hold and move the specimen in and out of the furnace. A pair of clamps/stoppers was installed on the transmission bar and attached to the transmission bar slider such that the transmission bar is controlled to move forward or backward. Another similar clamp was attached to the incident bar as a bar stopper to ensure that the incident bar stayed in place while the transmission bar was pushing the specimen forward in contact with the incident bar.

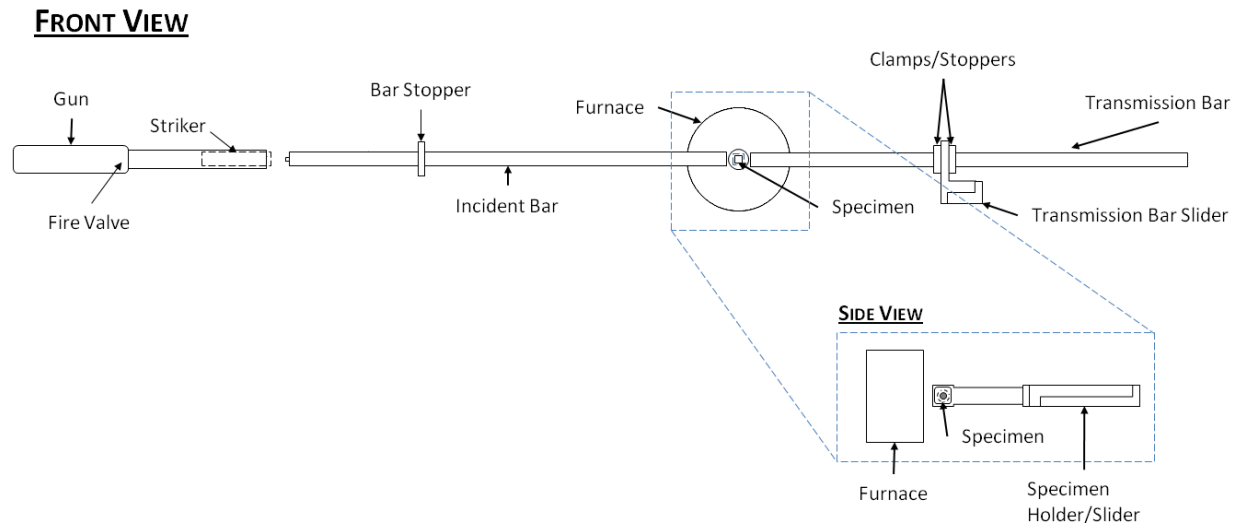
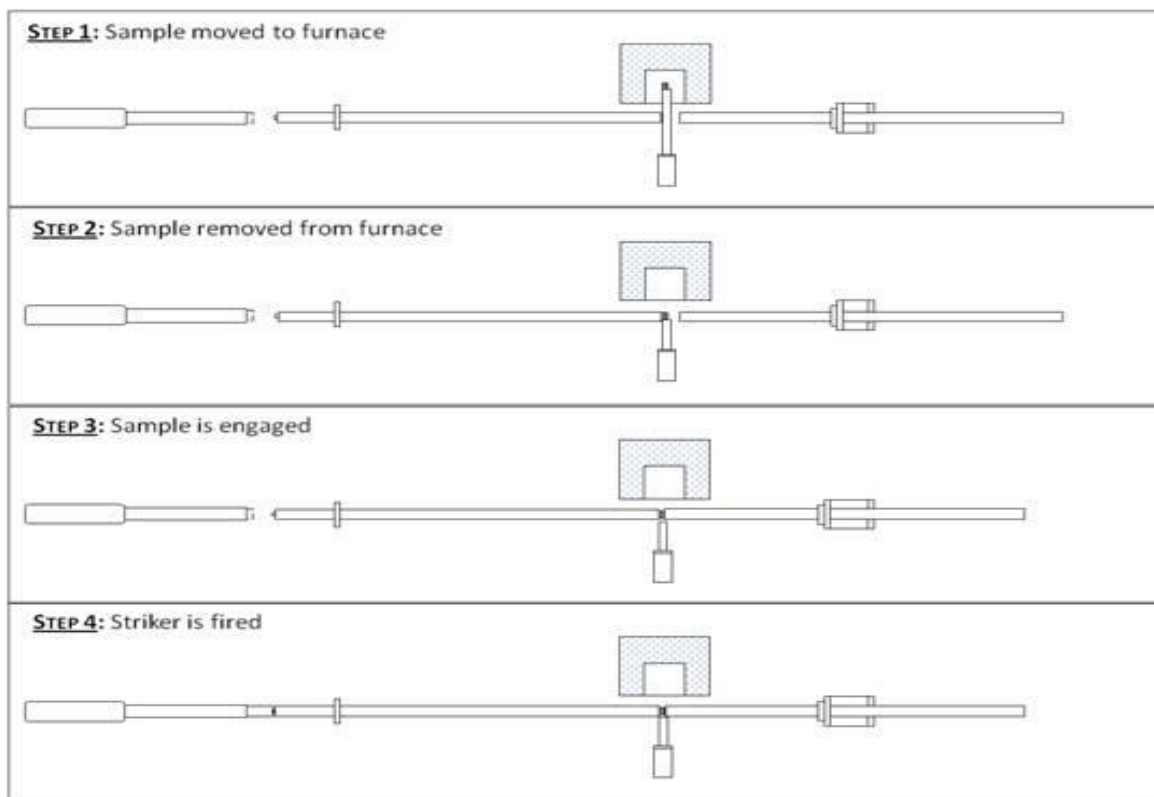


Figure 3. Schematic of automated high-temperature Kolsky compression bar system.

Figure 4 shows the sequence of steps of the automated high-temperature Kolsky bar system. Both the incident and transmission bars are initially separated from the specimen and the specimen holder. The pneumatic slider then sends the specimen and its holder into the furnace for heating (Step 1). When the desired specimen temperature is reached, the pneumatic slider moves the specimen and its holder out of the furnace and aligns the specimen center with the bar system axis (Step 2). This positioning process was controlled with a proximity sensor on the pneumatic slider. The pneumatic slider on the transmission bar immediately moves the transmission bar forward to put the transmission bar, the specimen, and the incident bar in contact. During this process, the incident bar is kept stationary by the bar stopper on the incident bar (Step 3). It takes a few milliseconds for the pneumatic slider to move the transmission bar forward to sandwich the specimen between the pressure bars. The fire valve on the gas gun is then opened and pushes the striker to impact the incident bar (Step 4). It takes several additional milliseconds for the striker to impact the incident bar once the fire valve is opened. The stress wave generated by this impact takes hundreds of microseconds to arrive at the incident bar/specimen interface to load the specimen. Note that the fire valve can be opened before or after the manipulator that moves the transmission bar forward has been activated. The principle is to load the specimen as soon as it is in contact with both pressure bars in order to have the shortest CCT. Opening the fire valve and activating the pneumatic slider on the transmission bar are precisely set through a computer software program. This method is capable of generating a CCT of only a few milliseconds.



**Figure 4. Operational steps for the high-temperature Kolsky compression bar testing.**

## 2.2. Issues in High-Temperature Kolsky Testing of Iridium

The automated high-temperature Kolsky bar system has been successfully utilized to obtain compressive stress-strain curves of 304L stainless steel at different elevated temperatures [10]. In that study [10], the stainless steel specimen had a diameter of 6.35 mm and a length of 3.175 mm, which is very typical for Kolsky bar experiments. However, additional issues need to be properly addressed when this automated high-temperature Kolsky bar is used to characterize a thin and smaller specimen such as the iridium alloy specimens in this study.

The iridium alloy specimens in this study were very thin, with a thickness of only 0.65 mm. In order to ensure that the specimen is compressed under an approximately 1-D stress state, the specimen diameter cannot be too large. In this study, a specimen diameter of 3-mm was selected. When such a small hot specimen makes contact with the “cold” (room-temperature) pressure bars, its temperature will drop much faster than that of a larger specimen. A series of thermal transfer analyses from high-temperature specimen to room-temperature pressure bars have been conducted.

The cool down of the high-temperature specimen in contact with room-temperature pressure bars was estimated using the series equation for an infinite plate subjected to a sudden cooling of its surfaces at a fixed temperature [11]. The temperature at a distance “x” from the center of the plate (or center of the iridium specimen) is:

$$T_x = T_s + (T_i - T_s) \left( \frac{4}{\pi} \right) \sum_{n=0}^{\infty} \left( \frac{1}{2n+1} \right) \exp \left( - \left( \frac{(2n+1)\pi}{2L} \right)^2 \alpha t \right) \sin \left( \frac{(2n+1)\pi x}{2L} \right) \quad (9)$$

where

$$\alpha = \frac{k}{\rho C_p} \quad (10)$$

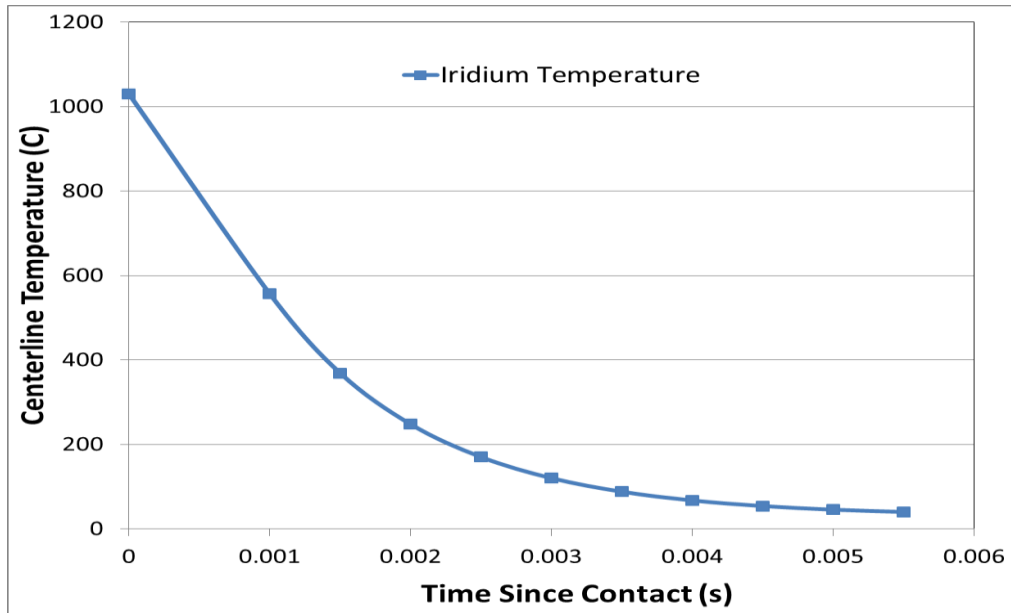
and

- $T_i$  is the initial temperature of the plate (or pressure bars) ( $^{\circ}\text{C}$ )
  - $T_s$  is the applied surface temperature of the plate (or pressure bars) ( $^{\circ}\text{C}$ )
  - $L$  is the half-thickness of the plate (or pressure bars) (m)
  - $t$  is the time since the plate (or pressure bars) started cooling (s)
  - $\alpha$  is the thermal diffusivity ( $\text{m}^2/\text{s}$ )
  - $k$  is the thermal conductivity of the plate (or pressure bars) ( $\text{W}/(\text{m} \cdot \text{K})$ )
  - $\rho$  is the density of the plate (or pressure bars) ( $\text{kg}/\text{m}^3$ )
  - $C_p$  is the specific heat capacity of the plate (or pressure bars) ( $\text{J}/(\text{kg} \cdot \text{K})$ )
- The material properties used in the analyses are listed in Table 1.

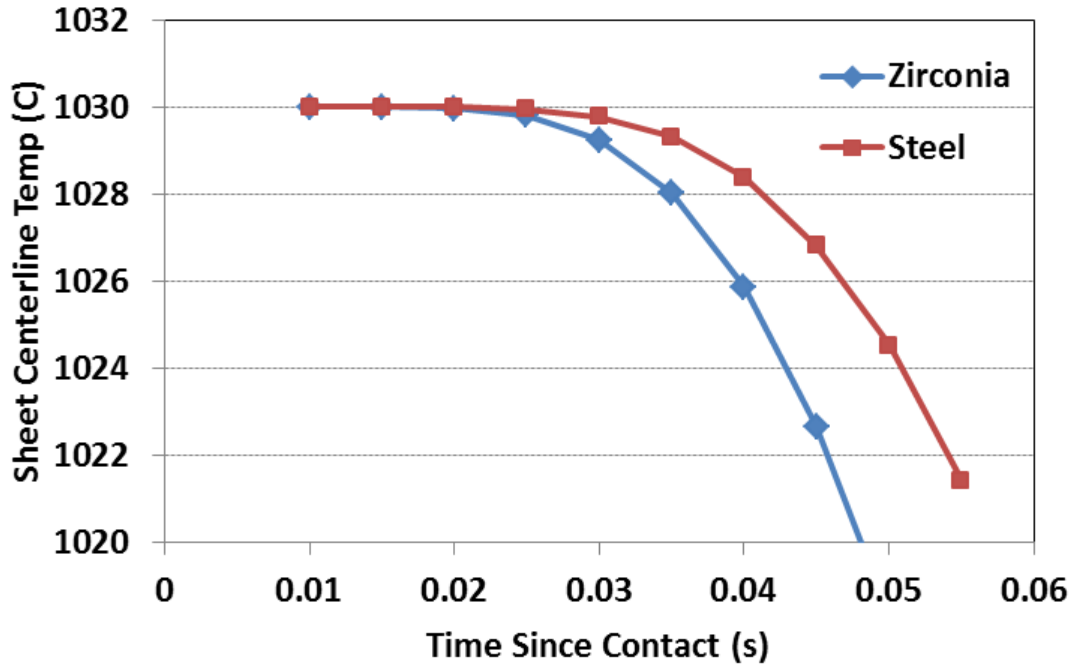
**Table 1. Material properties used for thermal analysis**

| Material                          | Iridium | Zirconia | Steel |
|-----------------------------------|---------|----------|-------|
| Half thickness (mm)               | 0.32    | 0.75     | 2.7   |
| Thermal conductivity (W/(m·K))    | 132     | 2        | 26    |
| Density (kg/m <sup>3</sup> )      | 22510   | 6000     | 8000  |
| Specific heat capacity (J/(kg·K)) | 160     | 450      | 400   |

For a thin iridium specimen held between two platens of significantly greater thickness and lower thermal conductivity, the overall thermal conductivity is governed by the material properties of the platens; therefore,  $L$  can be assumed to be equal to the thickness of one platen. The iridium temperature is approximately equal to the plate temperature at  $x=0$ . For an iridium alloy specimen with an initial temperature of 1030°C, Figure 5 shows its cooling rate after it comes into contact with the room-temperature steel pressure bars. As shown in Fig. 5, the temperature of the iridium specimen drops by 500°C within only 1 millisecond. This means that the CCT needs to be controlled in the order of microseconds, which significantly challenges the current automated high-temperature Kolsky bar system.



**Figure 5. Temperature change of an iridium alloy specimen after contact with the pressure bars.**

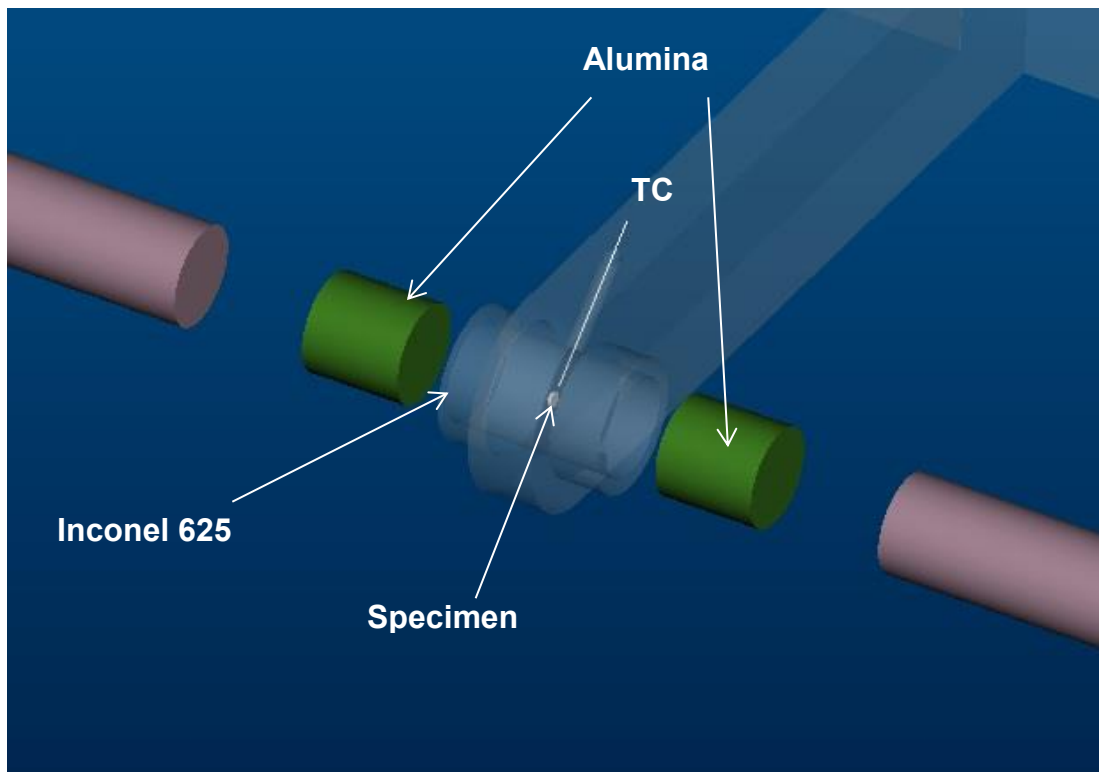


**Figure 6. Comparison of the cool-down histories of iridium specimens sandwiched between different platen materials**

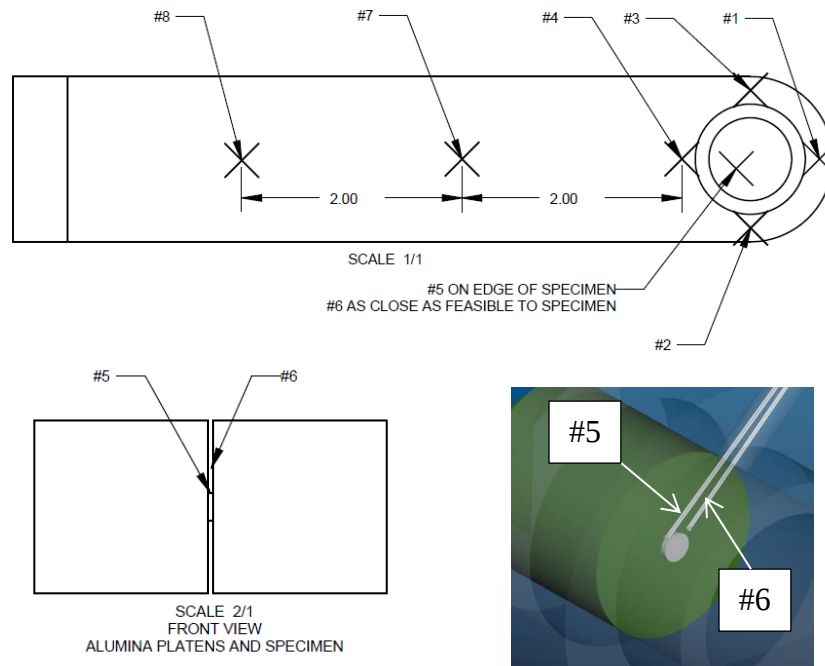
An alternative method is to heat a sandwich structure, which uses a pair of large platens to sandwich an iridium specimen. In this case, the heat transfer may start from the platens instead of the iridium specimen such that the iridium specimen temperature could be maintained for a longer duration. Figure 6 shows a comparison of cool-down histories when the iridium specimen is sandwiched between two different platen materials: zirconia and maraging steel respectively. The material properties of the zirconia and maraging steel used in the analyses are listed in Table 1. The initial temperature was set at the same value, 1030°C. Due to the introduction of the insulating platens, the iridium specimens were able to maintain the temperature for times as long as 20-30 milliseconds, which can be easily controlled with the current automated high-temperature Kolsky bar system. This duration could be even longer when thicker platens are used.

Since the platens are heated together with the iridium specimen in the furnace, the platen material should maintain high strength at high temperatures to prevent possible plastic indentation by the iridium specimen. However, neither zirconia nor steel shown in Fig. 6 are capable of maintaining high strength at the temperatures of interest, therefore they could not be used in this study. Instead, non-porous alumina (96-99.8%  $\text{Al}_2\text{O}_3$ ) was selected as the platen material due to its high stiffness and strength at high temperatures. Visual observation after preliminary dynamic testing at 1030°C confirmed the absence of indentation/plastic deformation or cracking.

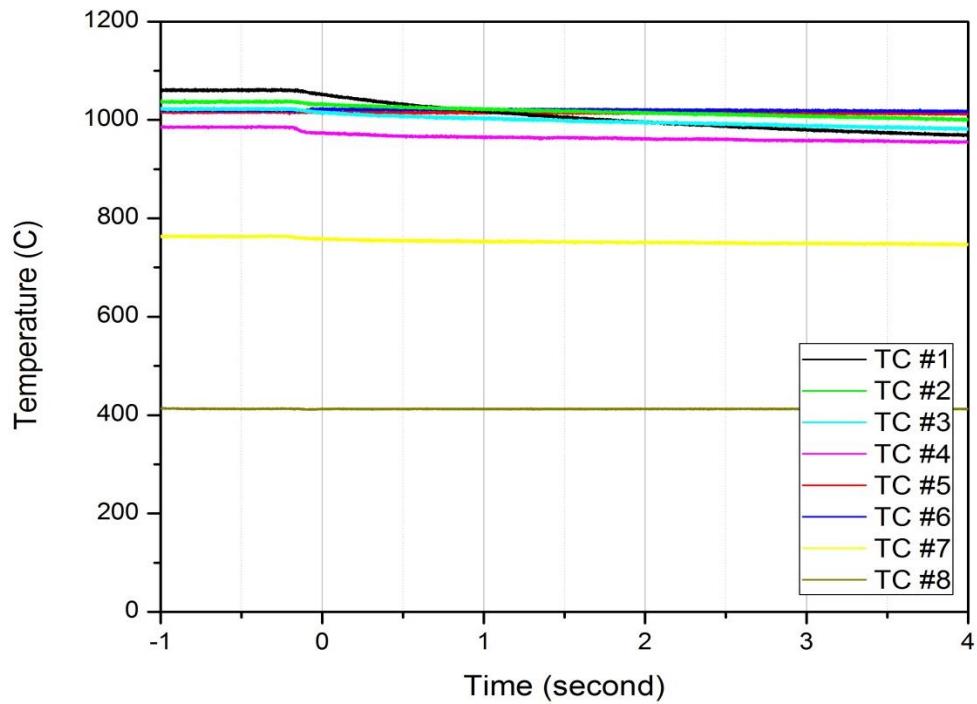
A pair of 19.05-mm-diameter, 25.4-mm-thick alumina platens with the specimen in between was held inside a tube made of Inconel 625. This tube was attached to a steel arm driven by a pneumatic slider, as shown in Fig. 7. This fixture configuration maintains the temperature of the iridium alloy specimen for times longer than 20-30 milliseconds after initial contact with the room-temperature pressure bars. However, there was concern that the temperature of the entire fixture would drop during the tens to hundreds of milliseconds that it typically takes for removal from the furnace and before contact can be made with the pressure bars. To address this issue, eight thermocouples were attached to different locations on the specimen holder and the specimen, as well as to the alumina ceramic platen surface, as shown in Fig. 8. Figure 9 shows the temperature histories recorded with these thermocouples after removal from the furnace. The temperatures decreased in a few seconds. Since the testing window is less than 200 milliseconds from specimen removal to dynamic loading, the fixture temperature does not change during this interval (Fig. 10) - particularly near the specimen edge as measured by thermocouple #5.



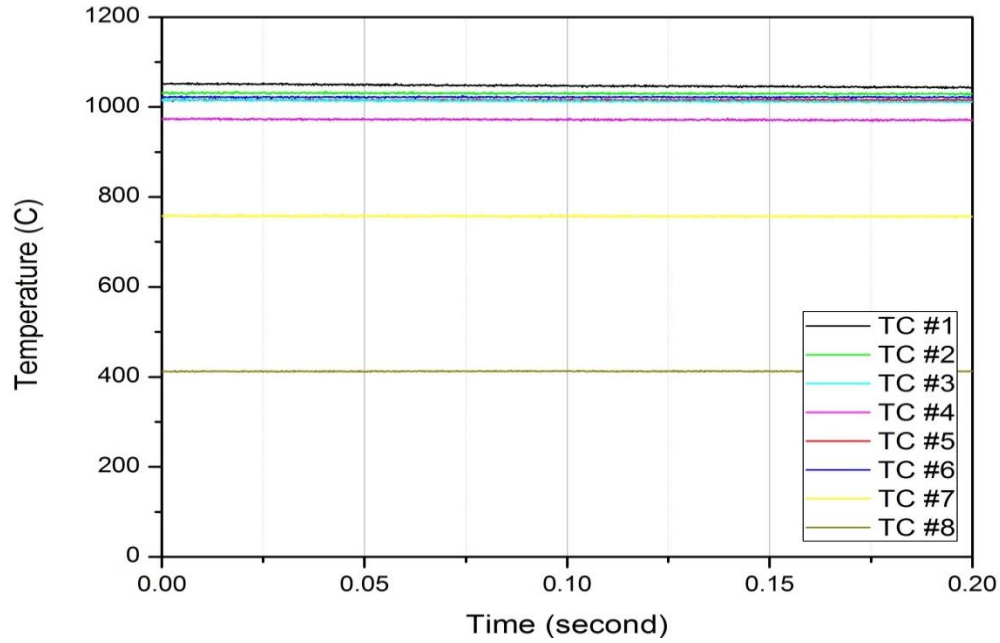
**Figure 7. Illustration of specimen fixture configuration.**



**Figure 8. Thermocouple locations.**



**Figure 9. Temperature histories at different locations.**



**Figure 10. Temperature histories at different locations within the time window of dynamic testing.**

Another important issue in the case of such a thin iridium alloy specimen is interfacial friction between the specimen and the bar ends at high temperatures. Interfacial friction can easily make the specimen deviate from a 1-D stress state, particularly when the specimen is very thin. An appropriate high-temperature lubricant should therefore be applied to the specimen end surfaces to minimize the interfacial friction. In this study, a super enhanced graphite (SEG) was selected for its superior lubrication performance particularly at high temperatures (Fig. 11) [12].

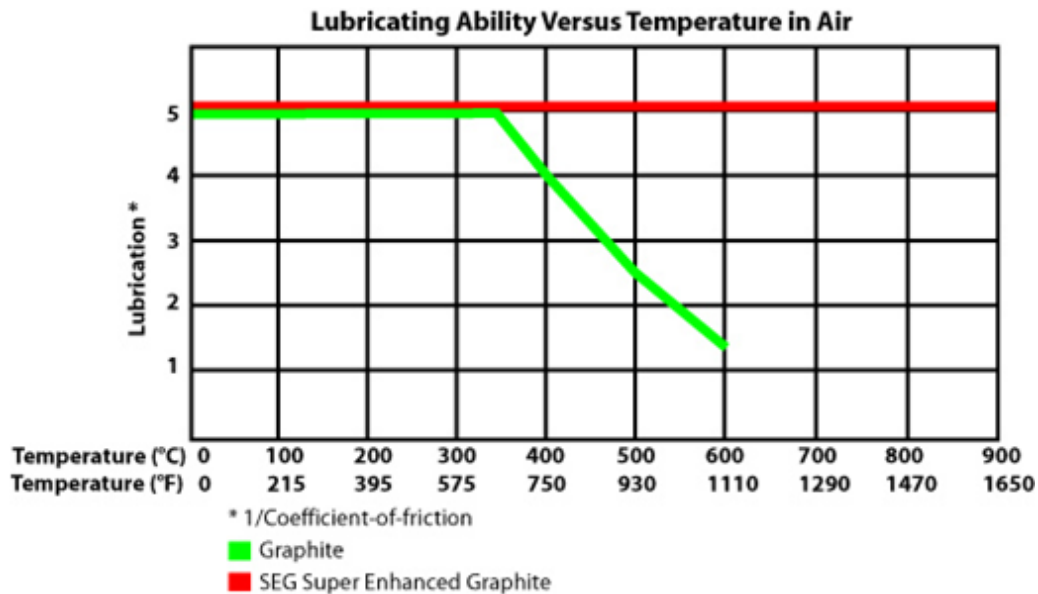
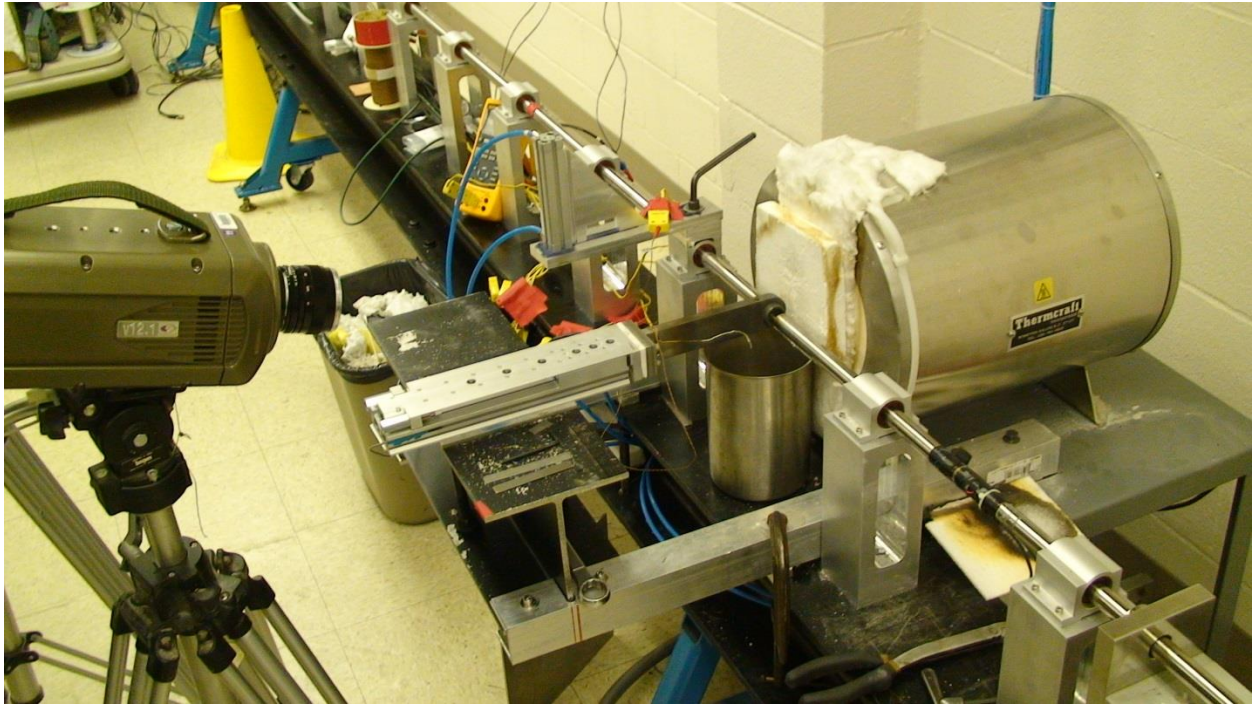


Figure 11. Lubrication performance of SEG graphite at high temperatures.

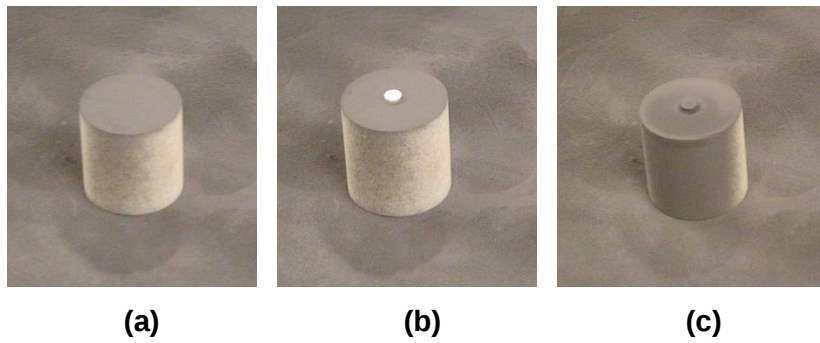
### 2.3. High-Temperature Kolsky Bar Design for Iridium Alloy Testing

Figure 12 shows the high-temperature Kolsky bar set-up for iridium alloy testing. The detailed installation stages are shown in Fig. 13. A thin layer of SEG was sprayed on the surface of an alumina platen (Fig. 13a). The iridium alloy specimen was then placed at the center of the alumina platen face (Fig. 13b). A second layer of SEG was sprayed on the iridium specimen and the alumina platen (Fig. 13c). This assembly (alumina platens plus iridium specimen) was inserted into an Inconel 625 tube attached to the arm of the specimen holder (Fig. 13d). Fig. 13d shows the small hole pre-drilled in the arm all the way through the Inconel 625 tube. A small Type K thermocouple was inserted into the hole and through the Inconel 625 tube so that the tip of the thermocouple was within 1 mm of the specimen. The second alumina platen, with the SEG-sprayed surface facing the iridium alloy specimen, was inserted into the Inconel 625 tube (Fig. 13e).

The entire specimen assembly was pushed into the resistance-heated furnace. An automatic temperature controller was located behind the Kolsky bar system. The Type K thermocouple was connected to a Fluke 724 temperature calibrator to monitor the specimen temperature during heating. The thermocouple signal was also recorded with a LeCroy high-speed digital oscilloscope during dynamic testing. A computer software program was developed for automated control of the high-temperature Kolsky bar experiments. The actuator and fire signals were recorded with a separate LeCroy high-speed digital oscilloscope for determining the CCT. The signals from the strain gages on the pressure bars were recorded with both oscilloscopes for data reduction and CCT determination.



**Figure 12. High-temperature Kolsky bar set-up for iridium testing.**



**Figure 13. Different stages in the installation of an iridium specimen.**

### 3. DYNAMIC HIGH-TEMPERATURE EXPERIMENTS

In this section, the dynamic high-temperature compression experiments performed on the iridium alloy at temperatures of 750°C and 1030°C and four different strain rates at each temperature are presented. The resultant compressive stress-strain curves were obtained and the temperature and strain rate effects on the compressive response of the iridium alloy were determined.

#### 3.1. Iridium Alloy Specimen Preparation

The iridium alloy specimens were prepared by ORNL. The disc specimens were removed from a prime 52-mm-diameter 0.65-mm-thick DOP-26 alloy blank using electrical discharge machining (EDM) with molybdenum wire, ground with a diamond abrasive to a final diameter of  $3.000 \pm 0.025$  mm to remove the residual EDM layer, weighed, and dimensionally inspected. The parallelism of specimen surfaces was controlled within 0.0025 mm.

The specimens were acid cleaned in a solution of 3 parts HCl and 1 part HNO<sub>3</sub> by volume, plus 15 vol. % HF for 30±10 minutes, followed by rinsing in distilled water and ethanol. The disc specimens were then re-weighed, heat treated at  $1375 \pm 25^\circ\text{C}$  for 1h±10 min in vacuum ( $\leq 1 \times 10^{-4}$  torr) in a furnace dedicated for the iridium alloy, and weighed again to verify identity.

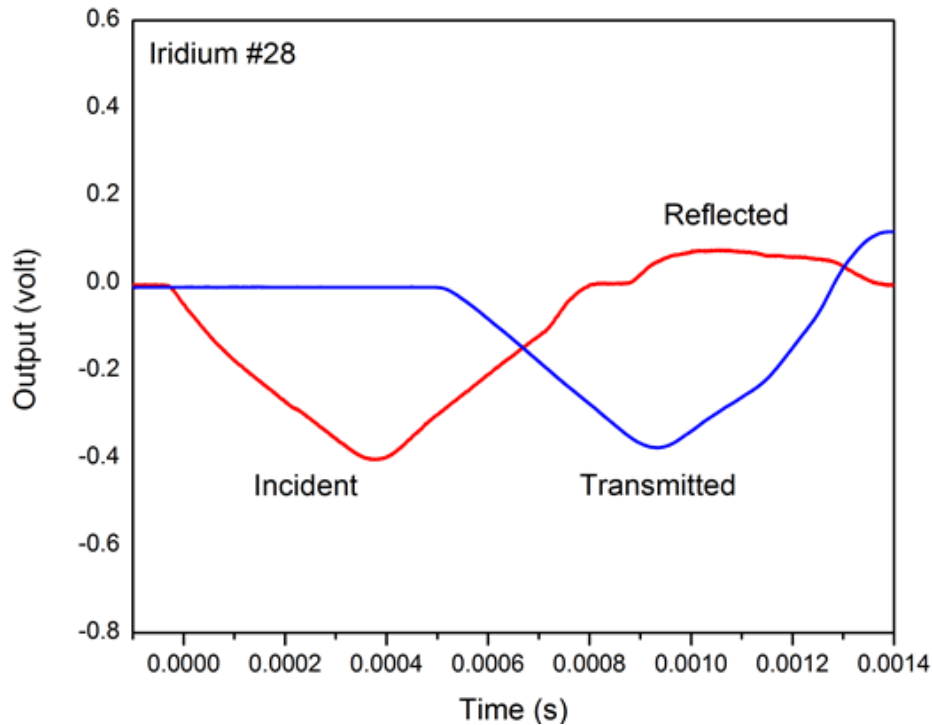
#### 3.2. Dynamic High-temperature Experiments

Dynamic high-temperature compression experiments on the iridium alloy were conducted at Sandia National Laboratories with the automated high-temperature Kolsky compression bar set-up shown in Fig. 12. At each temperature (750°C and 1030°C), dynamic compression tests were conducted at four different strain rates, approximately 300, 1000, 3000, and 10000/s, by varying the striker length and material as well as the striking speed. A summary of dynamic testing conditions is listed in Appendix A. Table 2 summarizes the strikers used for the tests at different strain rates. The longer strikers were used for lower strain rate tests to generate a longer duration of loading and relatively large deformation in the iridium alloy specimens. The pulse shaper material (stainless steel or annealed copper) and dimensions were also properly varied for each condition to facilitate dynamic stress equilibrium and constant-strain-rate deformation in the specimen.

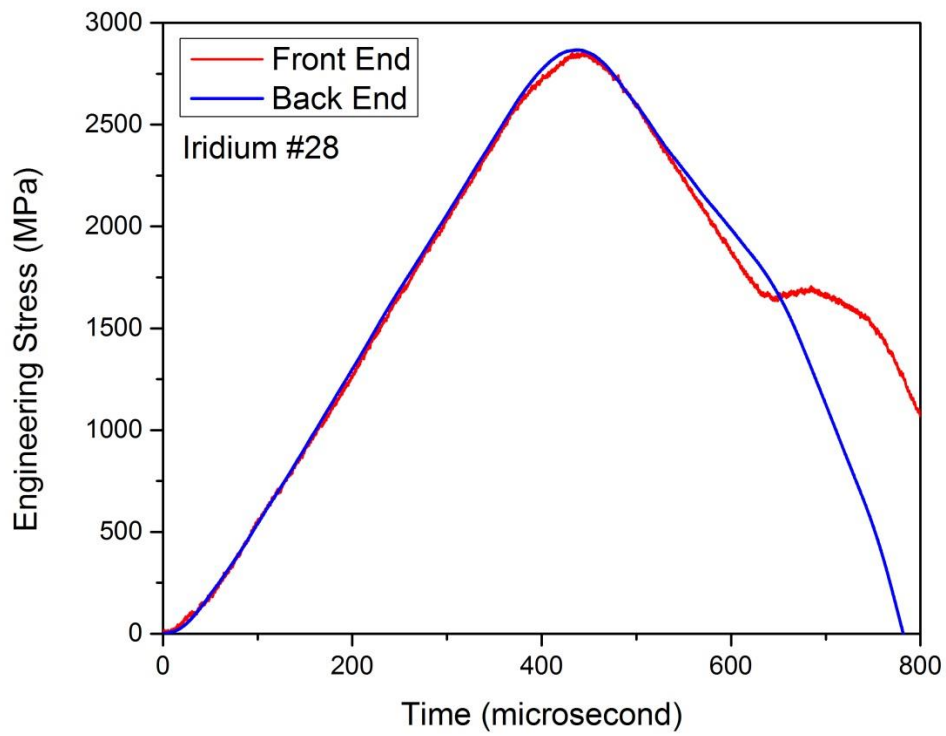
**Table 2. Striker dimensions for different strain rate tests**

| Strain Rate (1/s) | Striker                    | Approximately Maximum Strain |
|-------------------|----------------------------|------------------------------|
| 10000             | 150-mm-long maraging steel | 45%                          |
| 3000              | 300-mm-long maraging steel | 35%                          |
| 1000              | 900-mm-long maraging steel | 30%                          |
| 300               | 1200-mm-long 7075 aluminum | 20%                          |

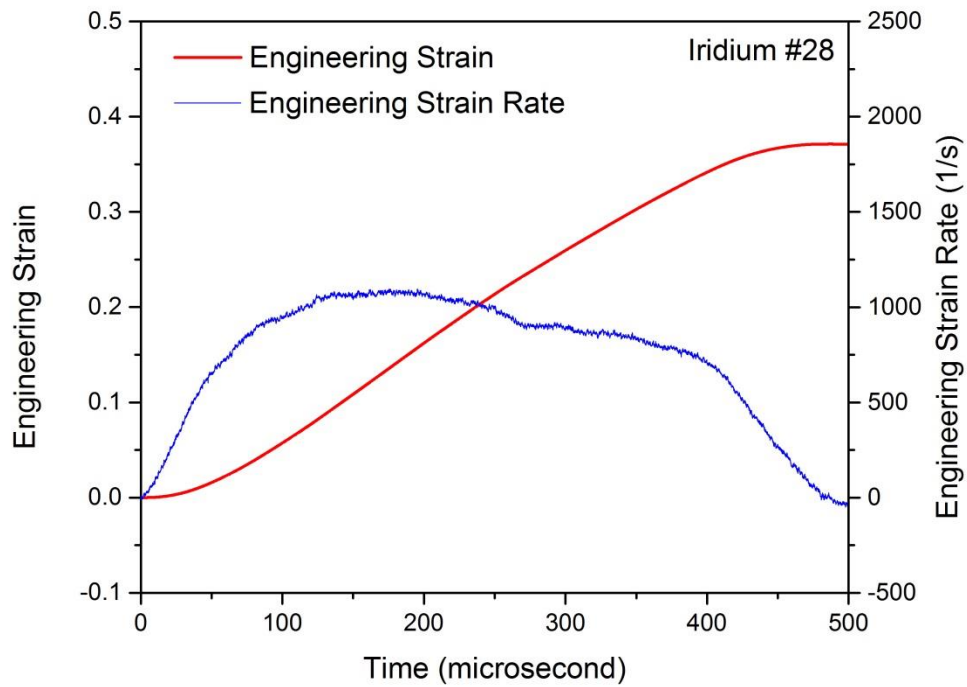
Figure 14 shows typical oscilloscope records of the incident, reflected, and transmitted signals from a compression experiment at 750°C. In this experiment, a  $\phi 3.65\text{mm} \times 0.45\text{mm}$  stainless steel disc was used as the pulse shaper which was placed on the impact end of the incident bar. Use of the pulse shaper significantly changed the profile of the incident pulse, which is very different from the square pulse in conventional Kolsky bar experiments. The modification of the incident pulse was done to achieve dynamic force/stress equilibrium and constant strain-rate deformation in the iridium alloy specimen. Figure 15 shows the stress histories at both ends of the specimen, which were calculated with Eqs. (3) and (4), respectively. The stress histories at both ends of the specimen nearly overlap, indicating that the specimen stress equilibrated due to proper pulse shaping. Figure 16 shows the strain-rate and strain histories in the specimen. The strain rate is an almost-uniform  $1000 \text{ s}^{-1}$  during dynamic loading, resulting in a nearly linear ramp in the strain history, indicating a successful change to the incident pulse profile. Figure 17 shows the temperature history measured with the thermocouple placed very close to the specimen as illustrated in Figs. 8 and 13d. The time has been synchronized to the stress and strain histories shown in Figs. 15 and 16, respectively. The desired testing temperature (750°C) was maintained over the entire duration of loading, demonstrating that the fixture design (Fig. 8) prevented a drop in the specimen temperature after contact between the high-temperature alumina-specimen “sandwich” and the room-temperature pressure bars. It must be noted that the thermocouple was not in direct contact with the iridium specimen, therefore, any adiabatic temperature rise in the specimen during dynamic loading would not be detected. The thermocouple was most likely in contact with the alumina platens and thus measuring the environmental temperature around the specimen.



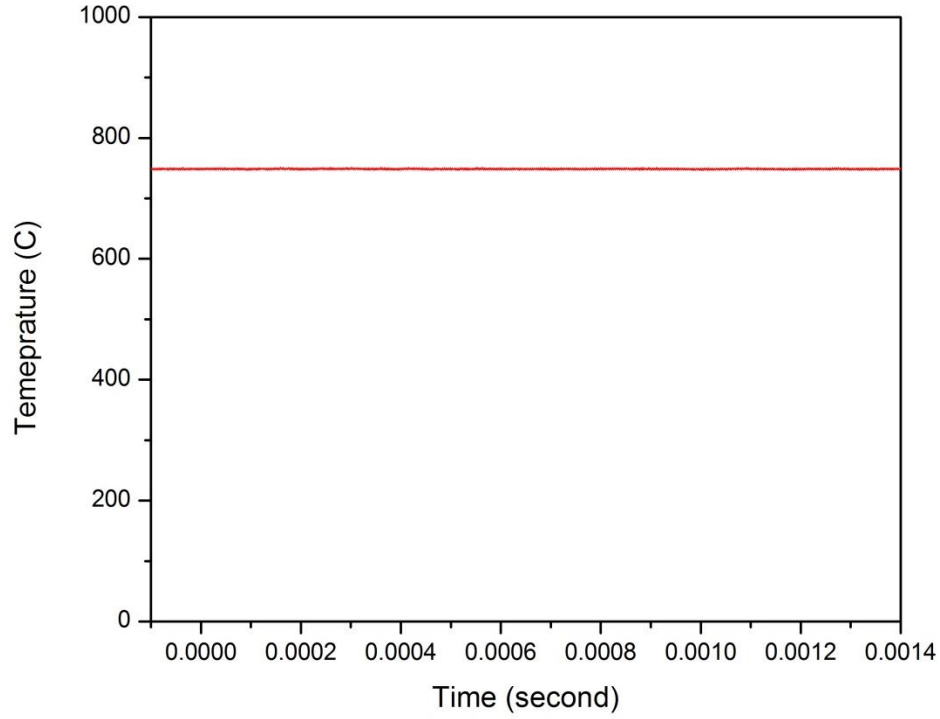
**Figure 14. Typical incident, reflected, and transmitted signals.**



**Figure 15. Dynamic stress equilibrium.**



**Figure 16. Strain-rate and strain histories.**



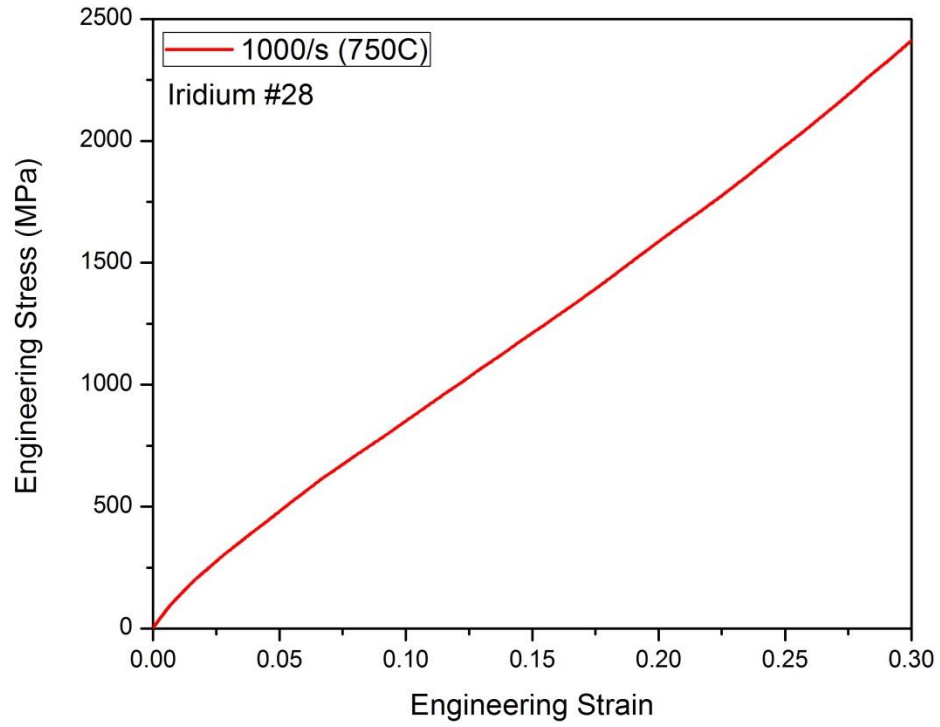
**Figure 17. Temperature history.**

Based on the calculated stress and strain histories shown in Figs. 15 and 16, the engineering stress-strain curve of the iridium alloy specimen were constructed by eliminating the time term. After the engineering stress-strain curve was calculated, the true stress-strain curve was calculated using the following equations for incompressible solids,

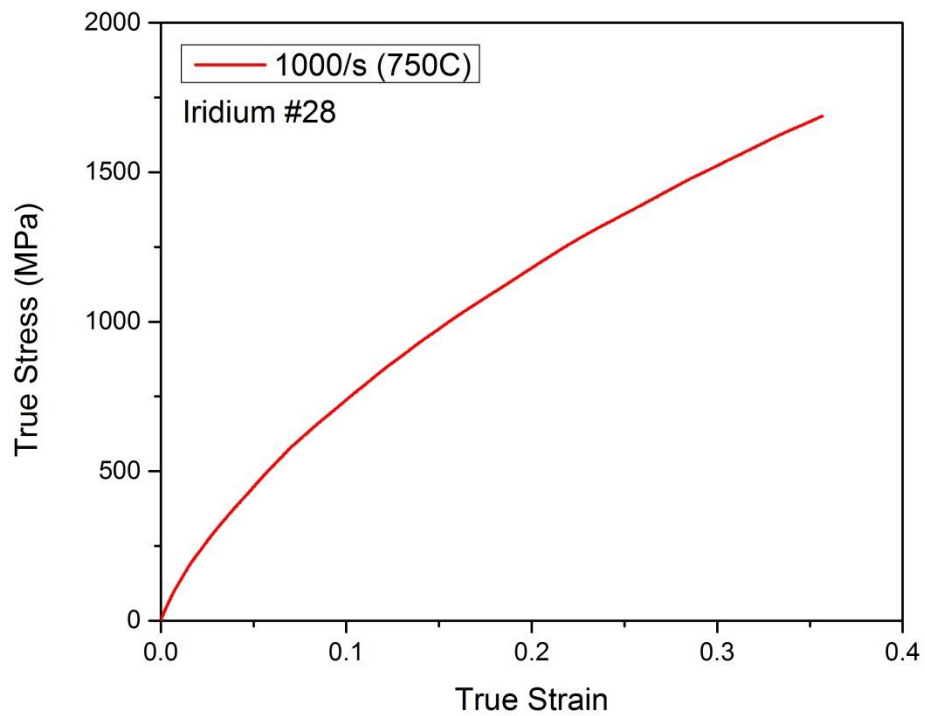
$$\sigma_T = (1 - \varepsilon)\sigma \quad (11)$$

$$\varepsilon_T = -\ln(1 - \varepsilon) \quad (12)$$

where  $\sigma_T$  and  $\varepsilon_T$  are true stress and true strain, respectively. Note that the sign is positive for compression here. Figures 18 and 19 show the engineering and true stress-strain curves of iridium at  $1000 \text{ s}^{-1}$  and  $750^\circ\text{C}$ , respectively. Both showed significant work hardening behavior.



**Figure 18. Representative engineering stress-strain curve at 1000/s, 750°C.**



**Figure 19. Representative true stress-strain curve at 1000/s, 750°C.**

### 3.3. Uncertainty Analysis

As shown in Fig. 8, two 1"-thick alumina platens were used to sandwich the iridium alloy specimen. The introduction of the two alumina platens may modify stress wave propagation, e.g., a stress wave reflection may occur at the steel bar/alumina platen interface. Such a reflection will be recorded with the strain gages on the incident bar, resulting in a wave mixture from the reflection at the platen/specimen interface. In other words, the specimen strain calculation based on the reflected wave recorded with the strain gages on the incident bar may include deformation of the two alumina platens, causing uncertainties in the calculation of the actual deformation and the stress-strain response of the iridium alloy specimen shown in Figs. 18 and 19.

Mechanical impedance match is critical to the propagation of an elastic stress wave through an interface between two media. The mechanical impedance is expressed as

$$I = \rho CA \quad (13)$$

where  $\rho$ ,  $C$ , and  $A$  are density, elastic wave speed, and cross-sectional area, respectively. For the C350 maraging steel bar used in this study at room temperature,  $\rho = 8100 \text{ kg/m}^3$ ,  $C = 4970 \text{ m/s}$ ,  $A = 285.023 \text{ mm}^2$ , which results in a mechanical impedance of

$$I_{\text{steel}} = 11400 \text{ kg/s} \quad (14)$$

For the alumina ceramic,  $\rho = 3875 \text{ kg/m}^3$ ,  $A = 285.023 \text{ mm}^2$ , and the elastic wave speed can be calculated as

$$C = \sqrt{\frac{E}{\rho}} \quad (15)$$

where  $E$  is Young's modulus. The Young's modulus of alumina has been observed to significantly decrease with increasing temperature, as shown in Fig. 20 [13]. From Fig. 20, the Young's moduli of alumina were determined to be  $\sim 330$  and  $315$  GPa at  $750^\circ\text{C}$  and  $1030^\circ\text{C}$ , respectively. Therefore, the mechanical impedance of alumina used in this study is

$$I_{\text{alum}} = \begin{cases} 10192 \text{ kg/s} & (750^\circ\text{C}) \\ 9958 \text{ kg/s} & (1030^\circ\text{C}) \end{cases} \quad (16)$$

which is approximately 10% lower than that of the steel pressure bars. The slight mechanical impedance mismatch between the steel bars and the alumina platens generates reflection factors of 0.056 at  $750^\circ\text{C}$  and 0.068 at  $1030^\circ\text{C}$ , respectively. This means that at  $750^\circ\text{C}$  and  $1030^\circ\text{C}$ , 5.6% and 6.8%, respectively, of the incident wave is reflected at the pressure bar/ceramic platen interface. It is noted that this estimation was based on a simple single interface between the pressure bar and the ceramic platen and did not account for multiple reflections of stress waves

within the alumina platens. In the latter case, it is difficult to precisely correct the effect of alumina platens on the resultant strain measurement of the iridium alloy specimen. However, the stress measurement in the iridium alloy specimen should not be affected.

An extreme condition was considered for the upper boundary of uncertainty due to the introduction of the alumina platens. The entire sandwich structure (two alumina platens and the iridium specimen) was treated as a single sample. The reflected pulse represented the total deformation of the whole sandwich structure. From Fig. 18, the iridium alloy specimen was subjected to 2400 MPa at a strain of 30%. Due to the force equilibration in the whole bar system, the alumina platens were subjected to the same force as the iridium alloy specimen, which was calculated to be 17000 N using the engineering stress and original cross-sectional area of the iridium alloy specimen. This force generated approximately 60 MPa in the alumina platen, which corresponded to a strain of 0.00018 at 1030°C. The alumina platens had a thickness of 19.05 mm each resulting in a total displacement in the two alumina platens of  $\delta = 0.00018 \times 19.05 \times 2 = 0.0069 \text{ mm}$ . This total displacement was equivalent to approximately 1% strain over the 0.65-mm-thick iridium alloy specimen. Therefore, within the total calculated strain of 30% in the iridium alloy specimen, a maximum strain of 1% might be attributable to the deformation of the two alumina platens. In other words, there was a maximum uncertainty of 3.3% in the strain measurement of the iridium specimen. This is acceptable, making it unnecessary to conduct additional Kolsky bar experiments for corrections.

Another uncertainty may result from possible elastic punching by the small-diameter iridium sample into the relatively large-diameter alumina platens. Safa and Gary [14] provided a guideline to correct the displacement from such a punching at a dynamically loaded bar end. Their analysis was used to estimate the uncertainty for the iridium testing. The specimen strain introduced by punching was calculated as

$$\varepsilon_{punch} = 2K_p \frac{\sigma \cdot A_s}{l_s} \quad (17)$$

where  $K_p = \frac{16}{3\pi^2} \frac{1-\nu^2}{dE_A} H_p \left( \frac{d}{D} \right)$ ;  $d$  and  $D$  are diameters of the specimen and the alumina platens, respectively;  $E_A$  and  $\nu$  are Young's modulus and Poisson's ratio of the alumina platens, respectively. The function,  $H_p \left( \frac{d}{D} \right)$ , was tabulated in Ref. [14].

In this study, we used  $D = 19.05 \text{ mm}$ ,  $E_A = 330 \text{ GPa}$ , and  $\nu = 0.5$  for the alumina platens. At the strain rate of  $1000 \text{ s}^{-1}$  and  $750^\circ\text{C}$  (Fig. 18), the relative errors were estimated as 9.3% and 10.8% at the measured 30% and 10% engineering strains, respectively. It is noted that the relative errors due to elastic punching are larger than those due to the wave reflection at the interface generated by the introduction of alumina platens, but smaller than the range (~15%-25%) of data scattering at the same condition. The relative errors are smaller at lower strain rates and higher temperature due to lower flow stresses. The uncertainty analyses above were used for informational purposes, and corrections were not made in this study.

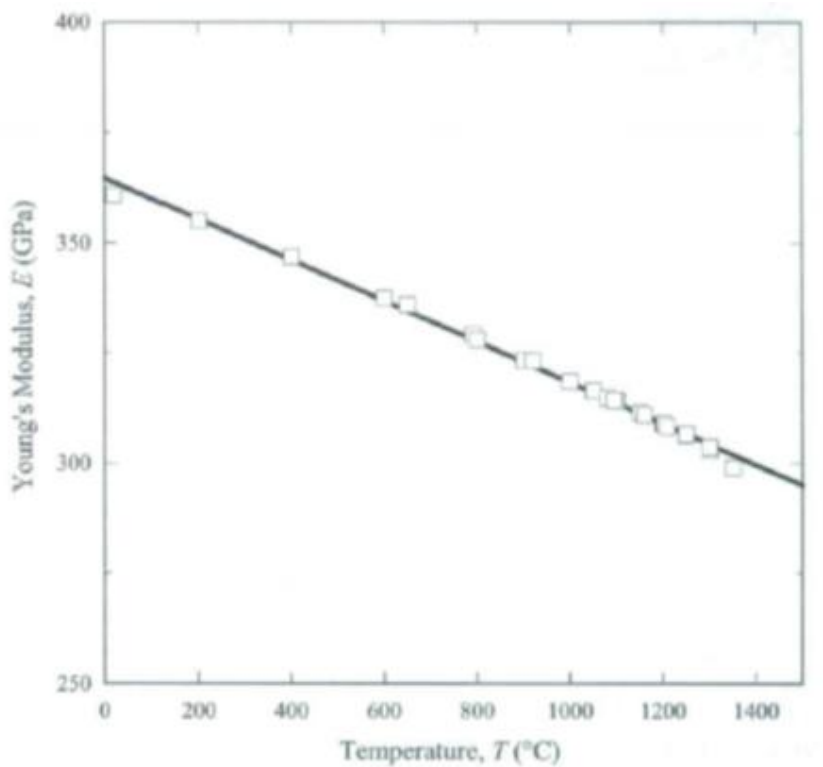


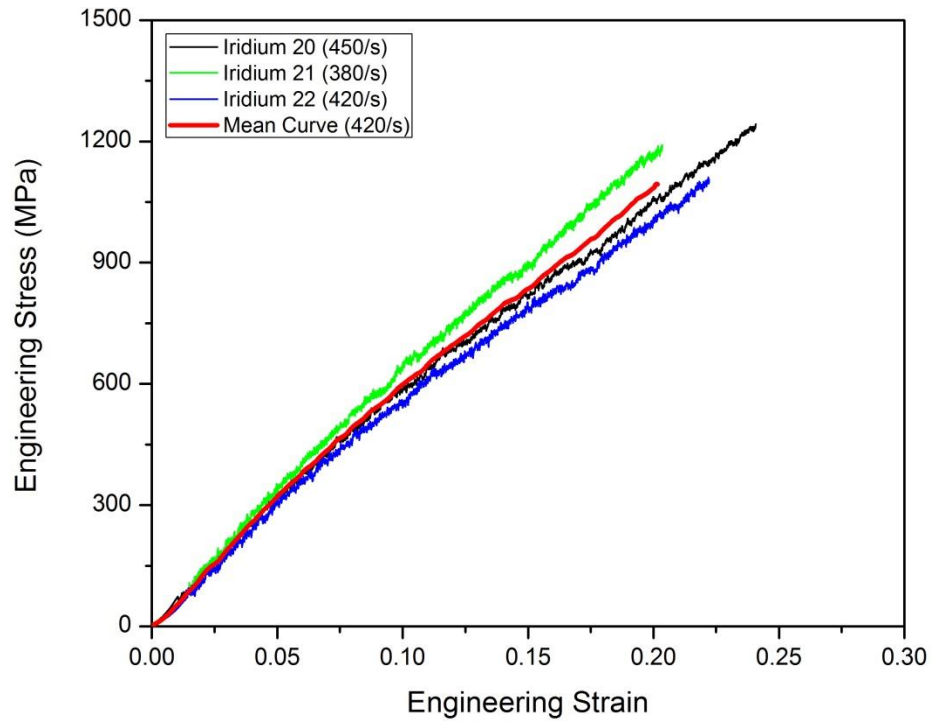
Figure 20. Young's modulus of alumina at high temperatures [13].

### 3.4. Experimental Results

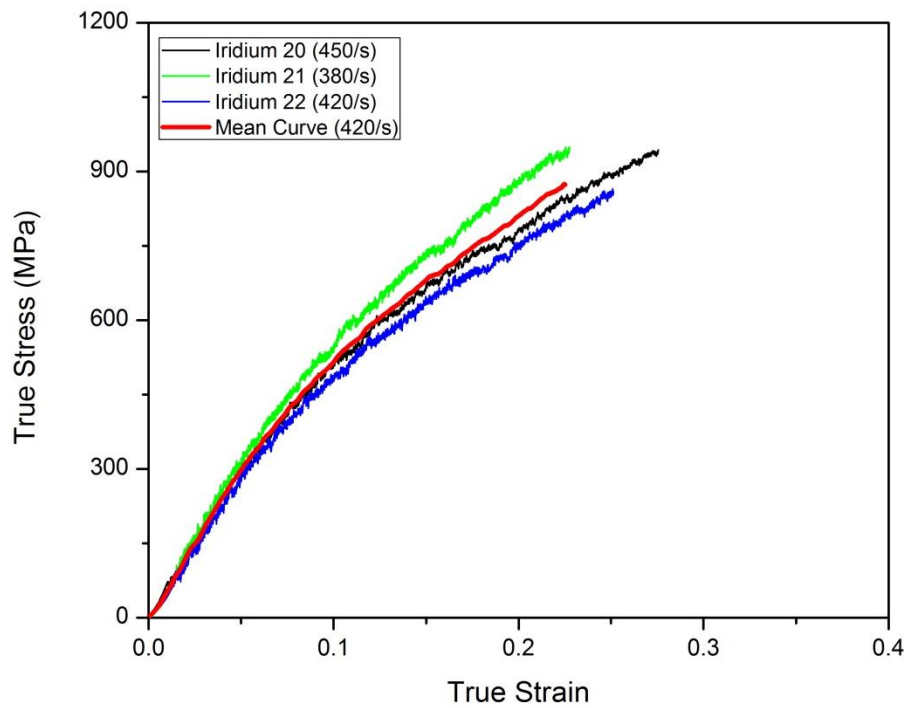
Following the procedure described above, the iridium alloy was characterized at strain rates of ~300, 1000, 3000, and 10000/s and temperatures of 750°C and 1030°C. As shown in Table 2, the striker length was increased for lower strain-rate testing to facilitate relatively large strains in the iridium alloy specimens.

Figures 21-28 show the resultant engineering and true stress-strain curves at various strain rates and temperatures. At each condition, three to four experiments were conducted to gauge reproducibility. At each testing condition, the individual curves from the three to four experiments and the corresponding mean curve are plotted in the same figure. The mean curves at 750°C and 1030°C are plotted in Figs. 29 and 30, respectively, to show the strain rate effect on the compressive response of the iridium alloy at each temperature. At each temperature, the iridium alloy showed significant strain rate dependence: the stress at a specific strain significantly increases with increasing strain rate. The iridium alloy also exhibits significant temperature dependence, when all the curves are plotted in the same figure (Fig. 31).

In order to examine the detailed strain-rate effect at the two temperatures, the flow stresses at engineering strains of 5%, 10%, 20%, and 25% were plotted versus strain rate as shown in Figs. 32 and 33. The solid dots and error bars in both Figs. 32 and 33 represent the mean value and data scattering of the three to four repeated experiments, respectively. Figure 34 shows both strain-rate and temperature effects on the compressive response at engineering strains of 5%, 10%, 20%, and 25%. It is noted that it takes time for the strain rate to reach the desired constant value, and this time significantly increases when pulse shaping is applied [15, 16]. Before a constant strain rate is achieved, the measured stress-strain response does not represent the actual material response at this constant strain rate and should not be used to investigate the strain-rate effect. As a consequence, the data at 5% strain for the strain rate of  $10000 \text{ s}^{-1}$  were not used because it took the strain rate at least 10 microseconds to ramp from zero to  $10000 \text{ s}^{-1}$ . When the strain rate reached  $10000 \text{ s}^{-1}$ , the accumulated strain was approximately 10%, which means that the stress-strain data below 10% strain did not represent the actual response of the iridium alloy at  $10000 \text{ s}^{-1}$ , but rather a lower-strain-rate response.

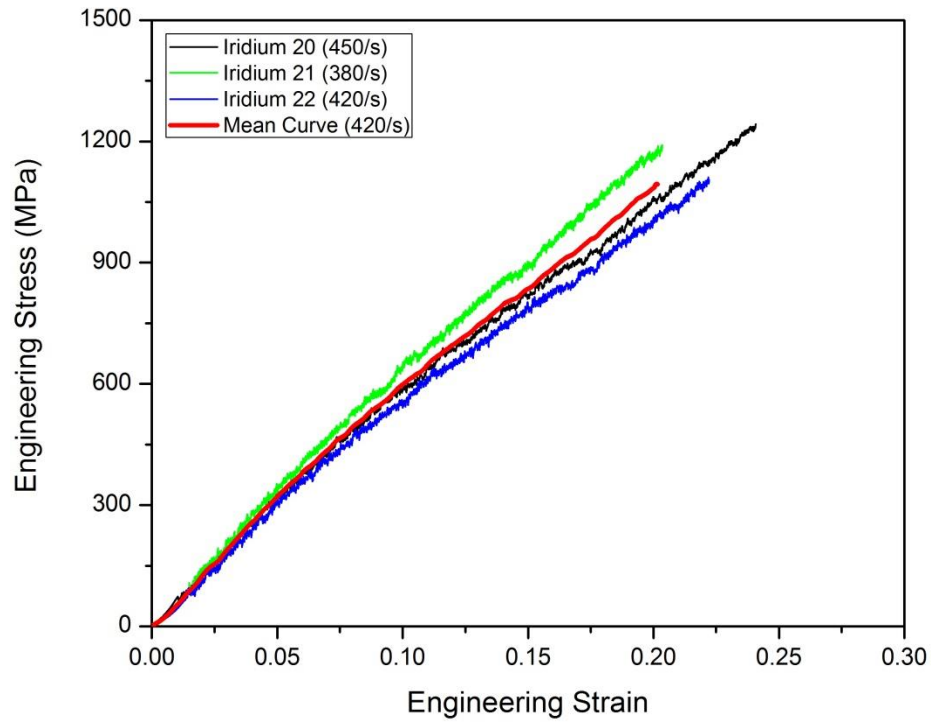


(a)

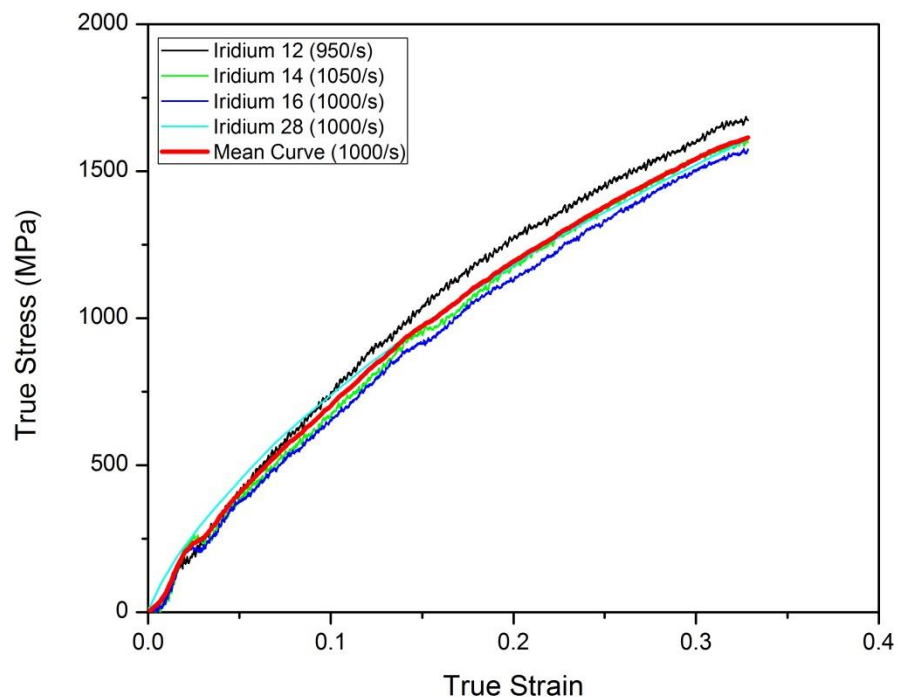


(b)

**Figure 21. Compressive stress-strain curves at 420/s, 750°C.**  
**(a) Engineering stress-strain curves; (b) True stress-strain curves**

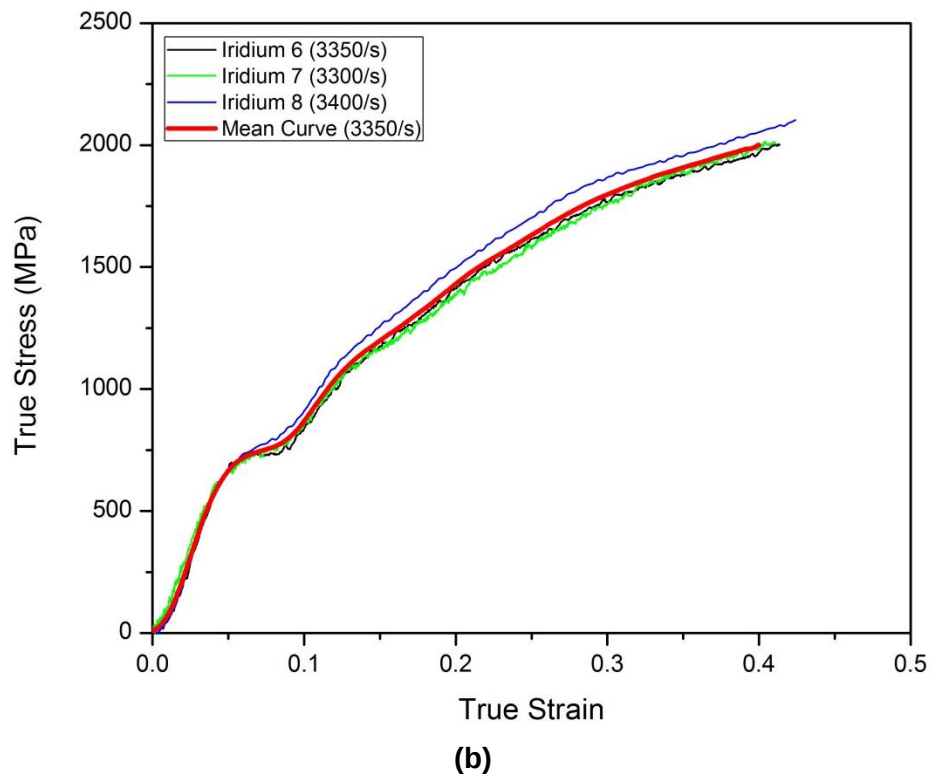
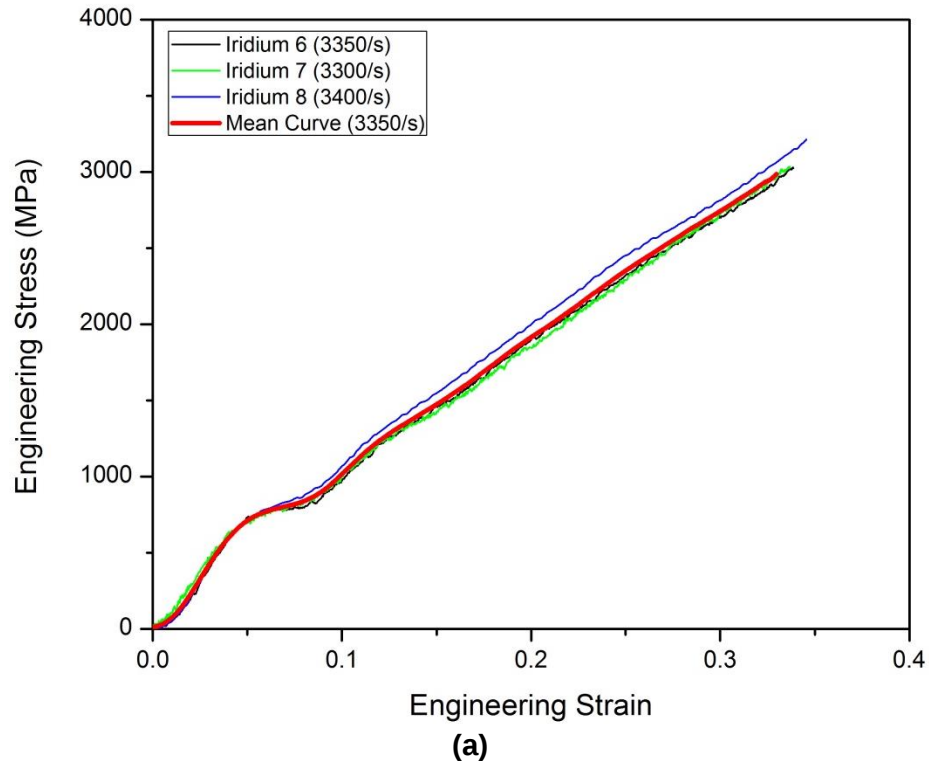


(a)



(b)

**Figure 22. Compressive stress-strain curves at 1000/s, 750°C.**  
**(a) Engineering stress-strain curves; (b) True stress-strain curves**



**Figure 23. Compressive stress-strain curves at 3350/s, 750°C.**  
**(a) Engineering stress-strain curves; (b) True stress-strain curves**

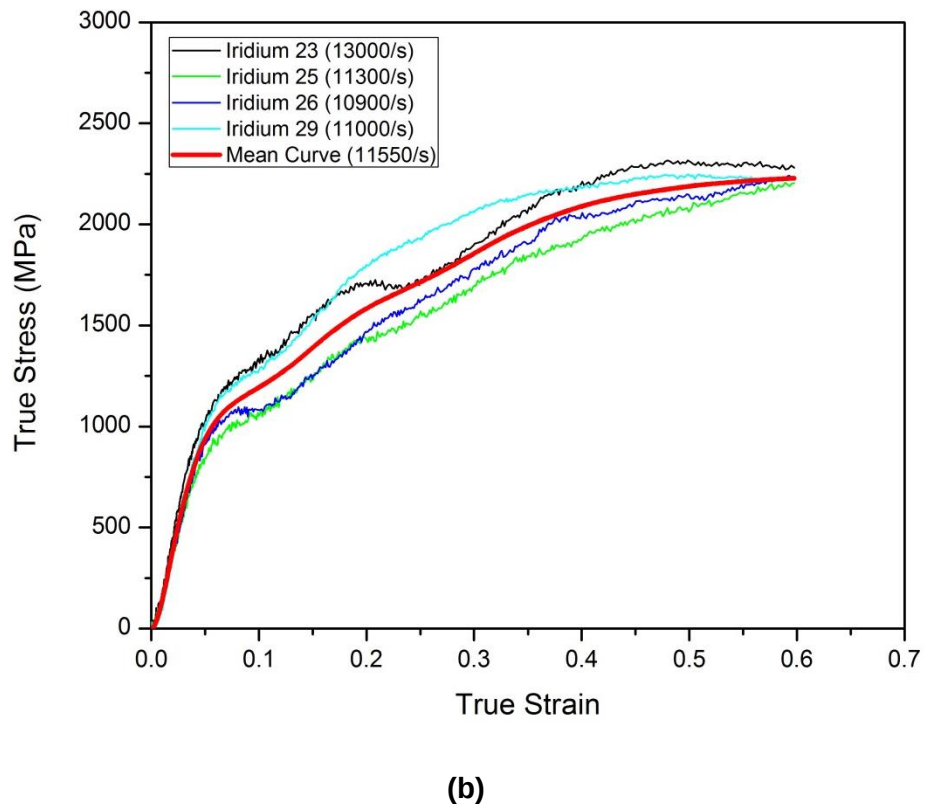
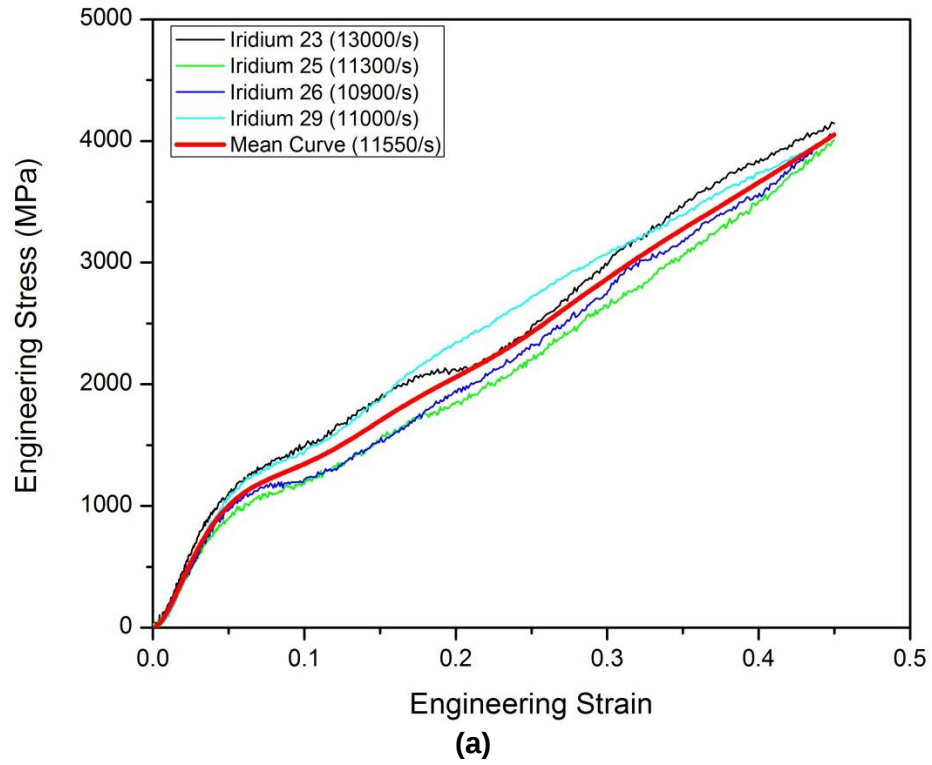
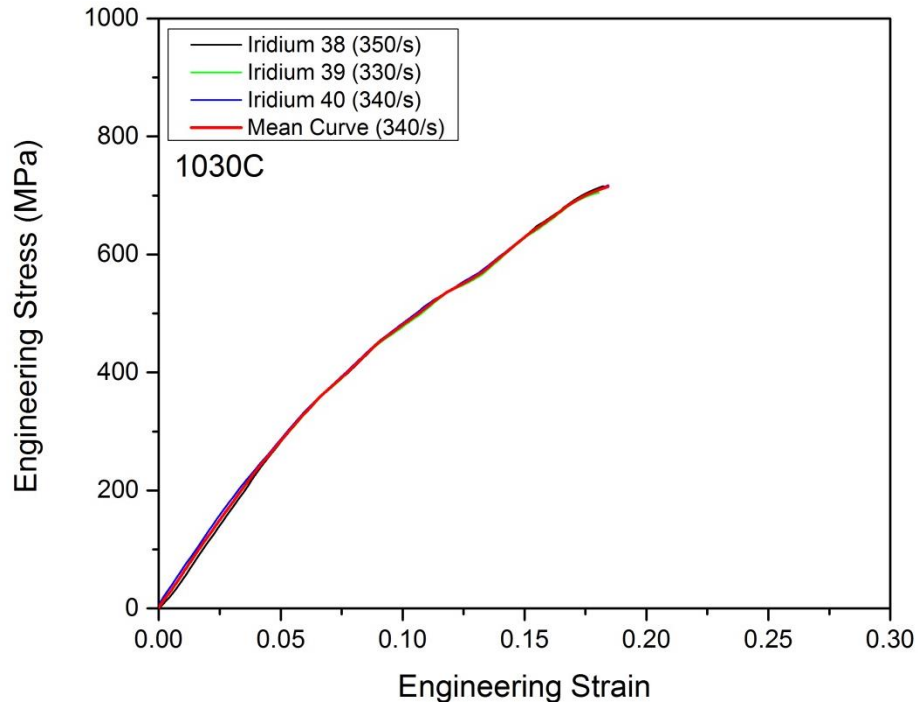
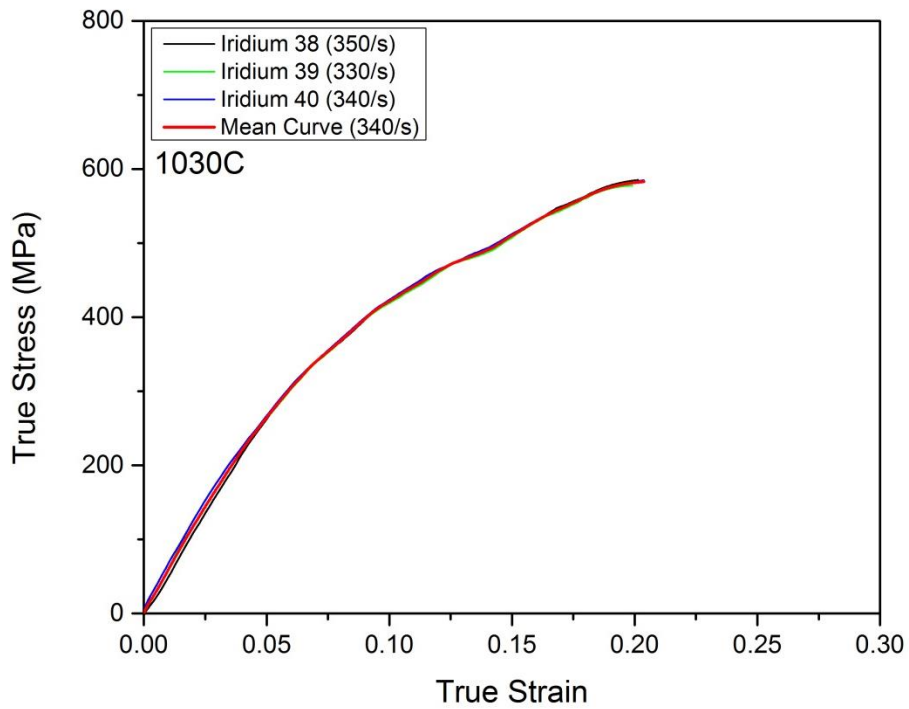


Figure 24. Compressive stress-strain curves at 11550/s, 750°C.  
(a) Engineering stress-strain curves; (b) True stress-strain curves



(a)



(b)

**Figure 25. Compressive stress-strain curves at 340/s, 1030°C.**  
**(a) Engineering stress-strain curves; (b) True stress-strain curves**

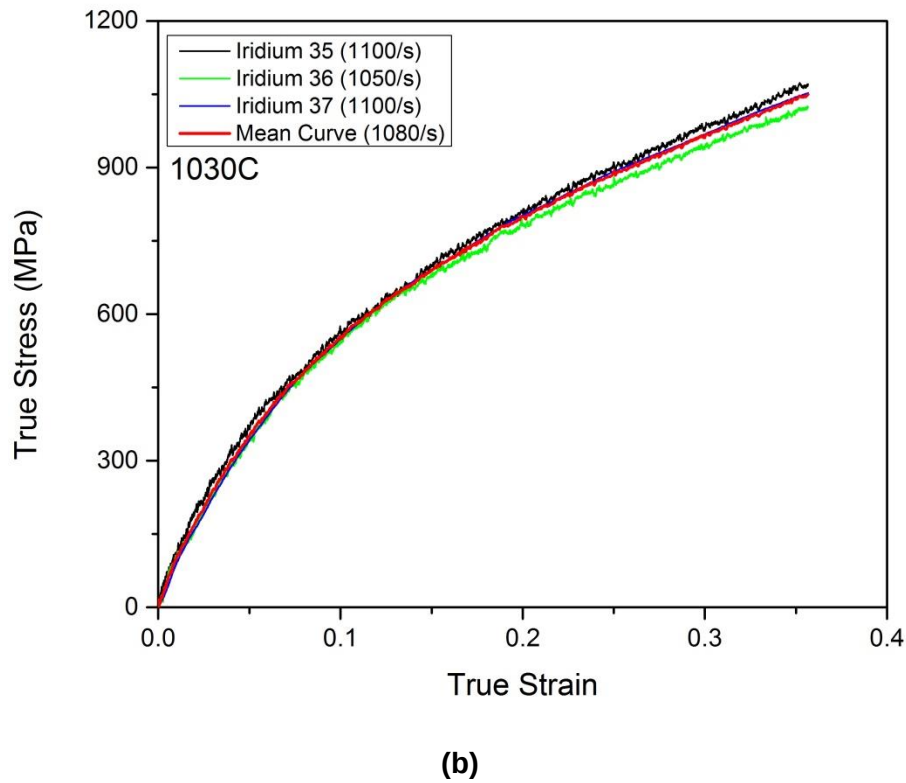
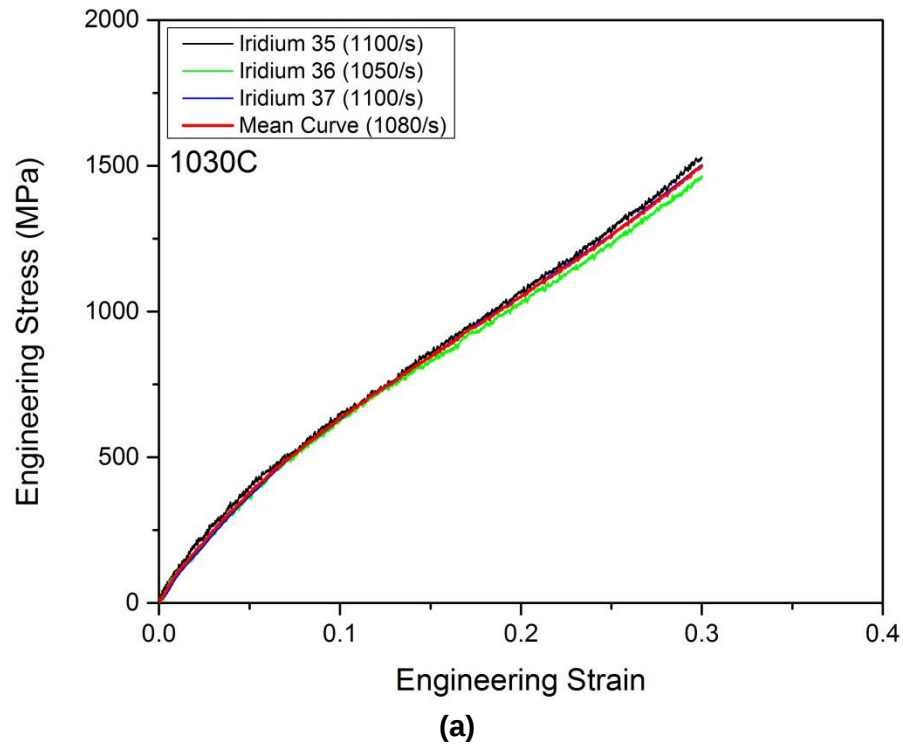
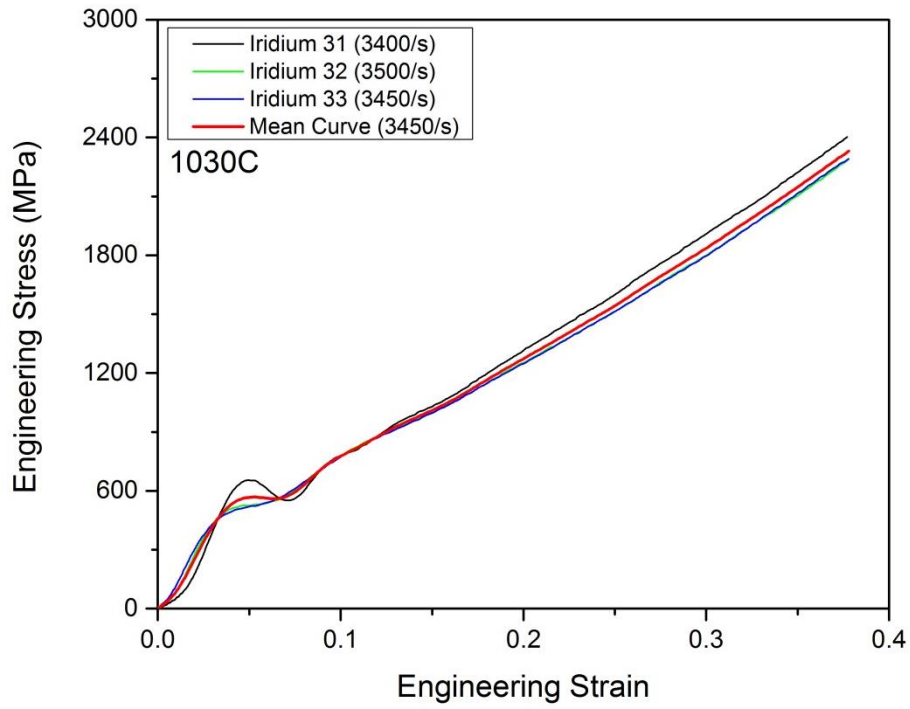
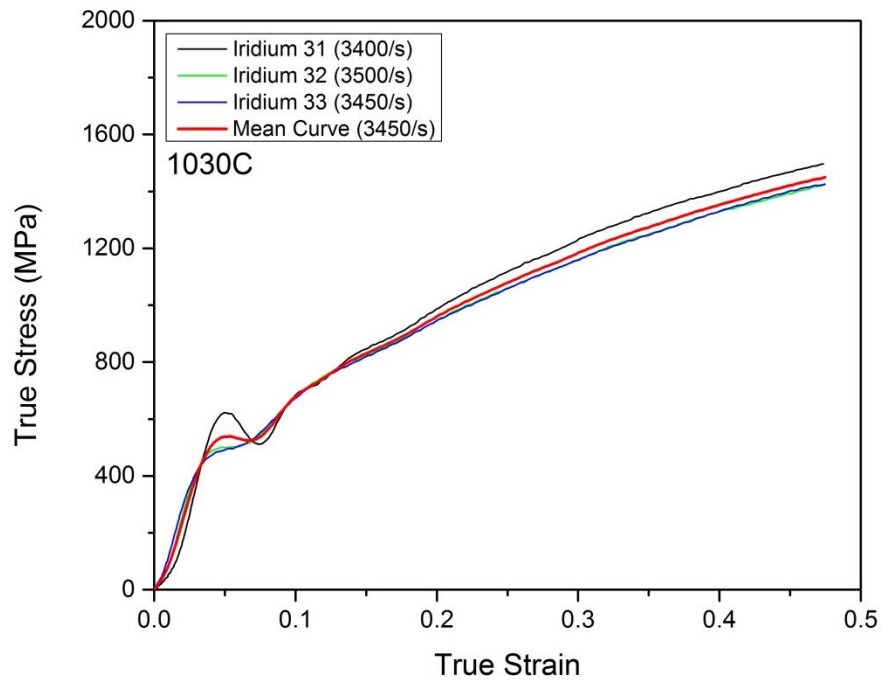


Figure 26. Compressive stress-strain curves at 1080/s, 1030°C.  
(a) Engineering stress-strain curves; (b) True stress-strain curves

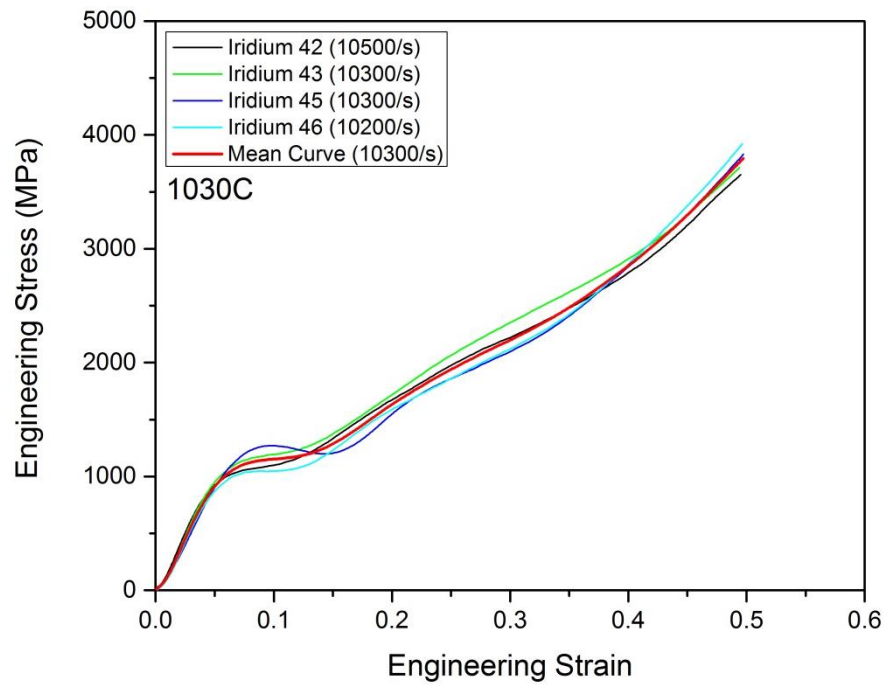


(a)

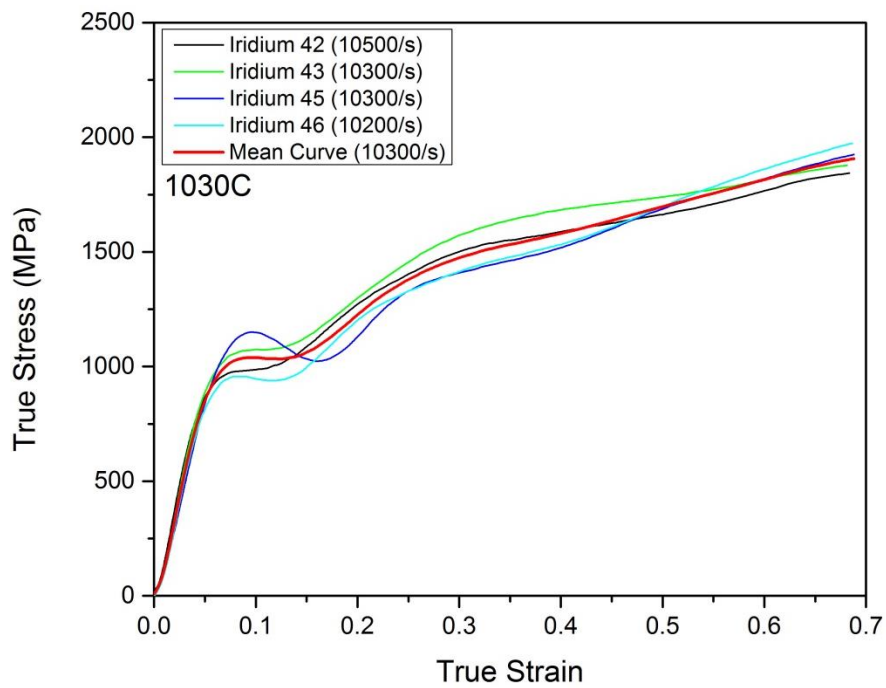


(b)

Figure 27. Compressive stress-strain curves at 3450/s, 1030°C.  
(a) Engineering stress-strain curves; (b) True stress-strain curves

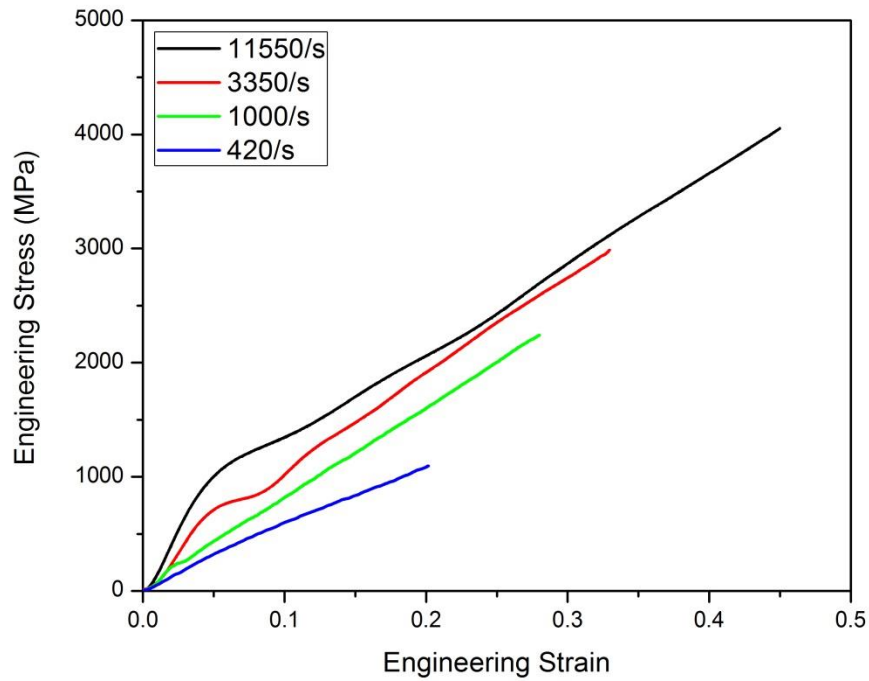


(a)

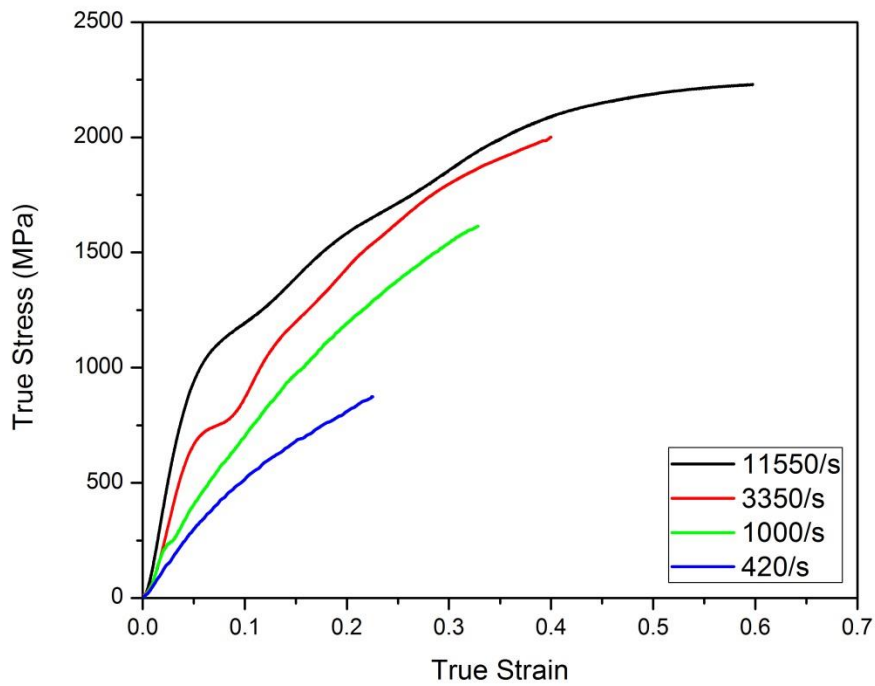


(b)

**Figure 28. Compressive stress-strain curves at 10300/s, 1030°C.**  
**(a) Engineering stress-strain curves; (b) True stress-strain curves**

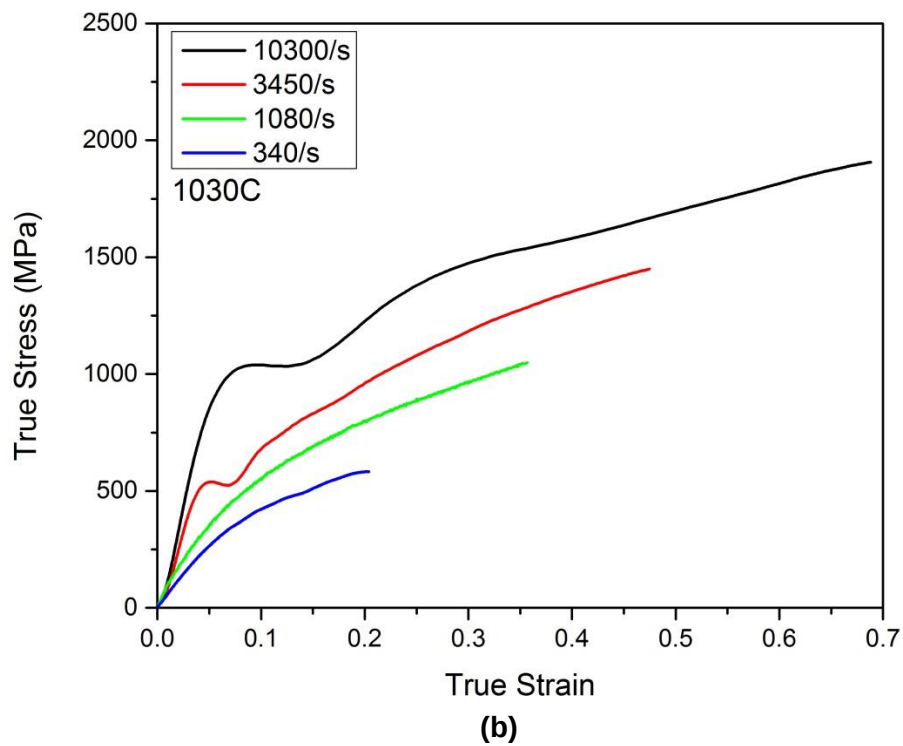
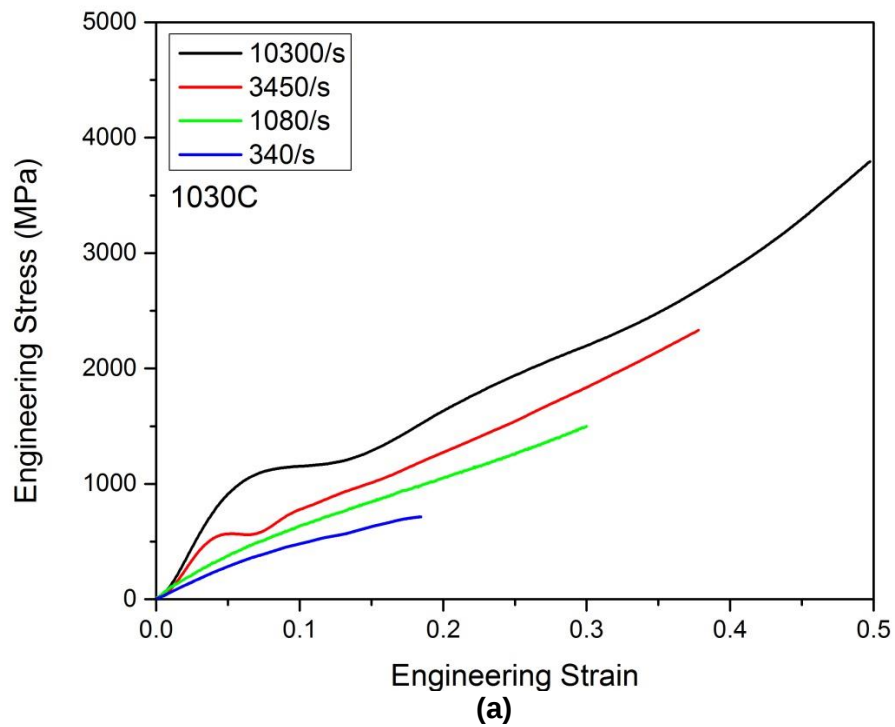


(a)

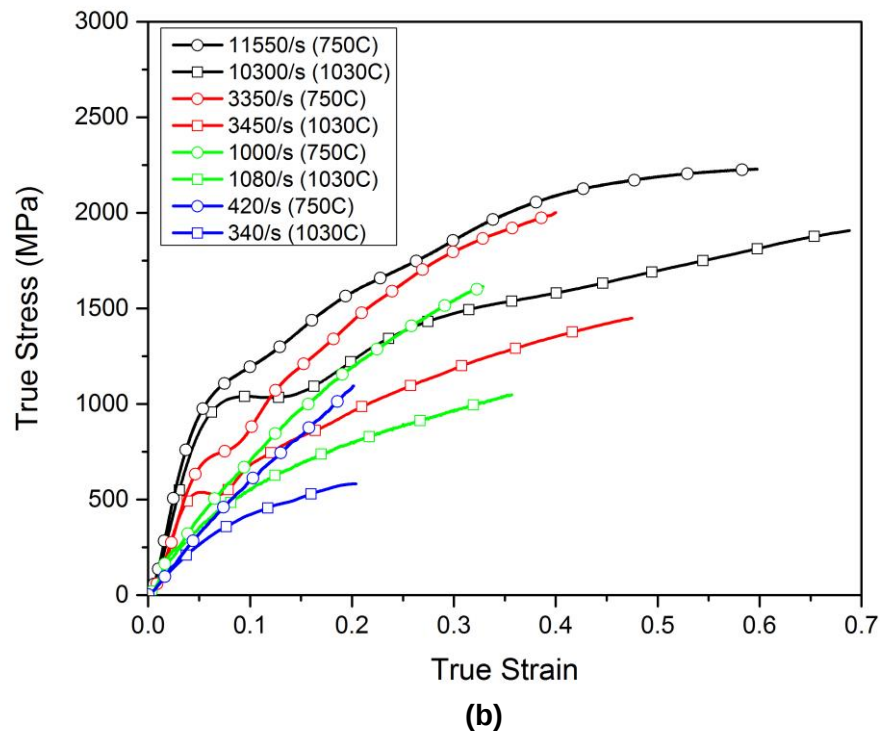
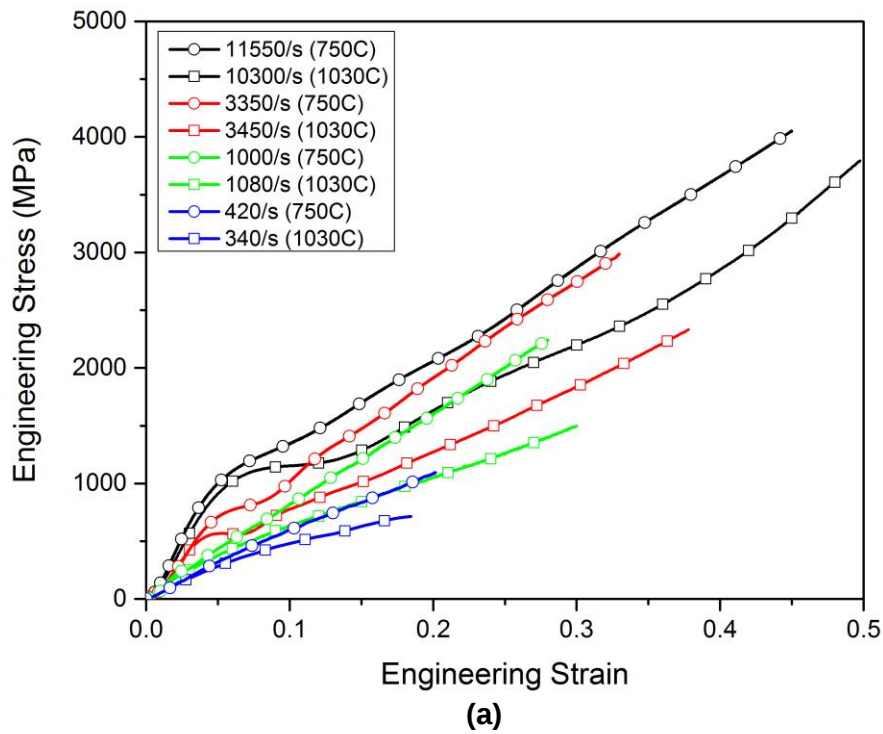


(b)

Figure 29. Compressive stress-strain curves at 750°C.  
(a) Engineering stress-strain curves; (b) True stress-strain curves



**Figure 30. Compressive stress-strain curves at 1030°C.**  
**(a) Engineering stress-strain curves; (b) True stress-strain curves**



**Figure 31. Temperature and strain rate effects**  
**(a) Engineering stress-strain curves; (b) True stress-strain curves**

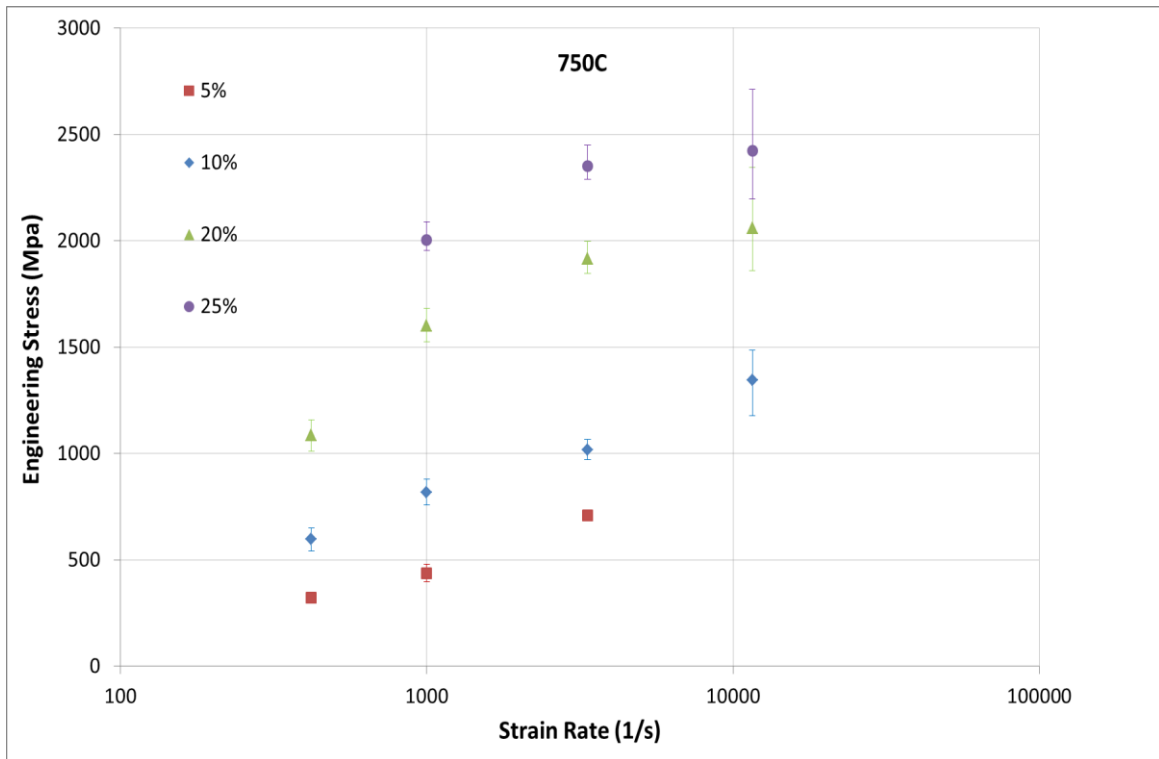


Figure 32. Strain rate effect at 750°C

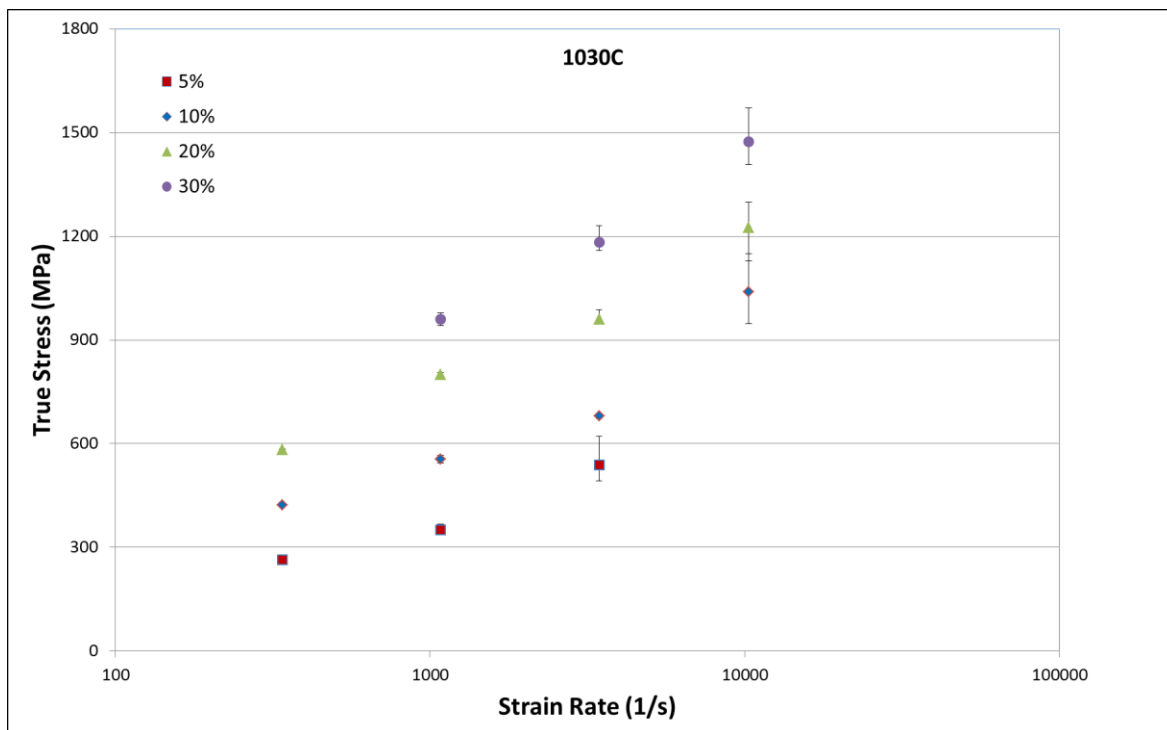
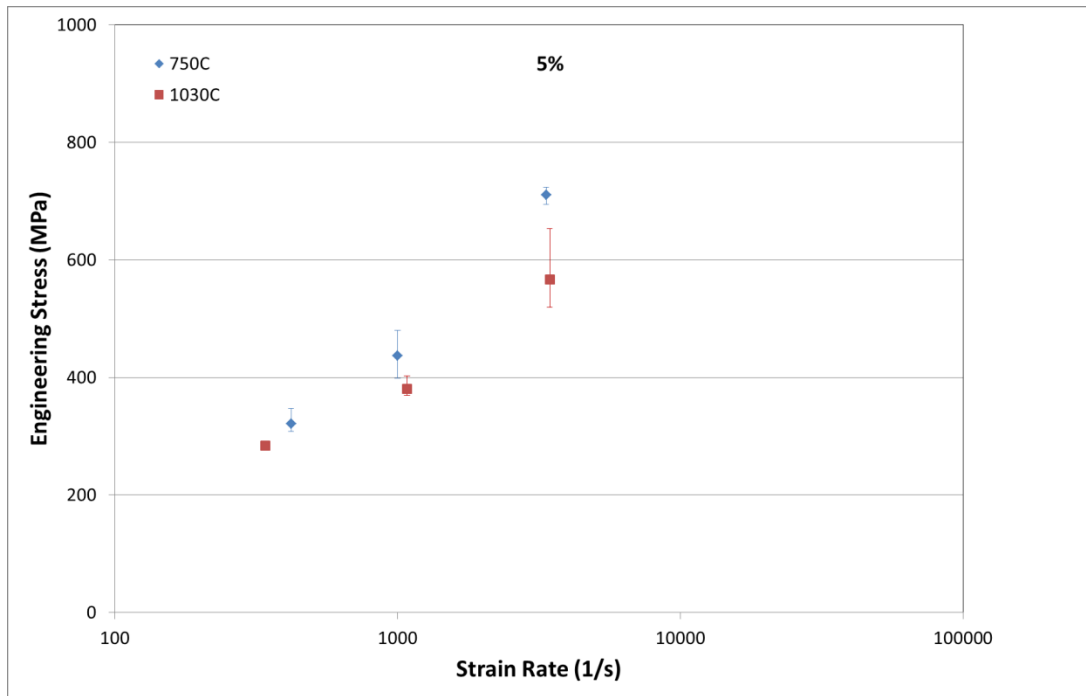
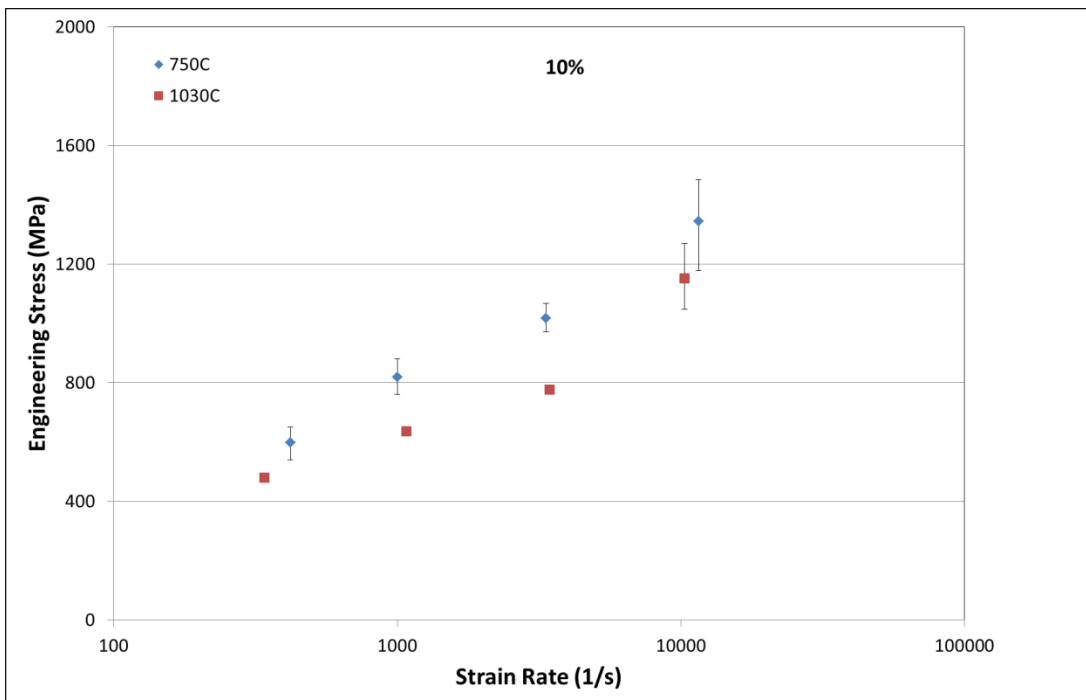


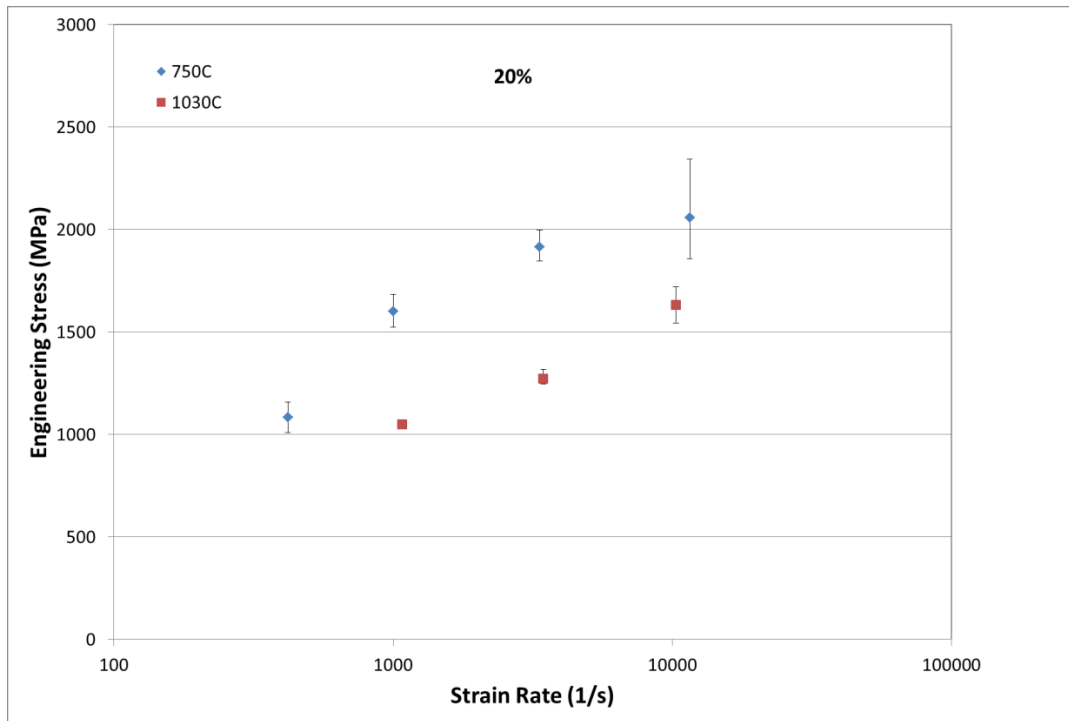
Figure 33. Strain rate effect at 1030°C



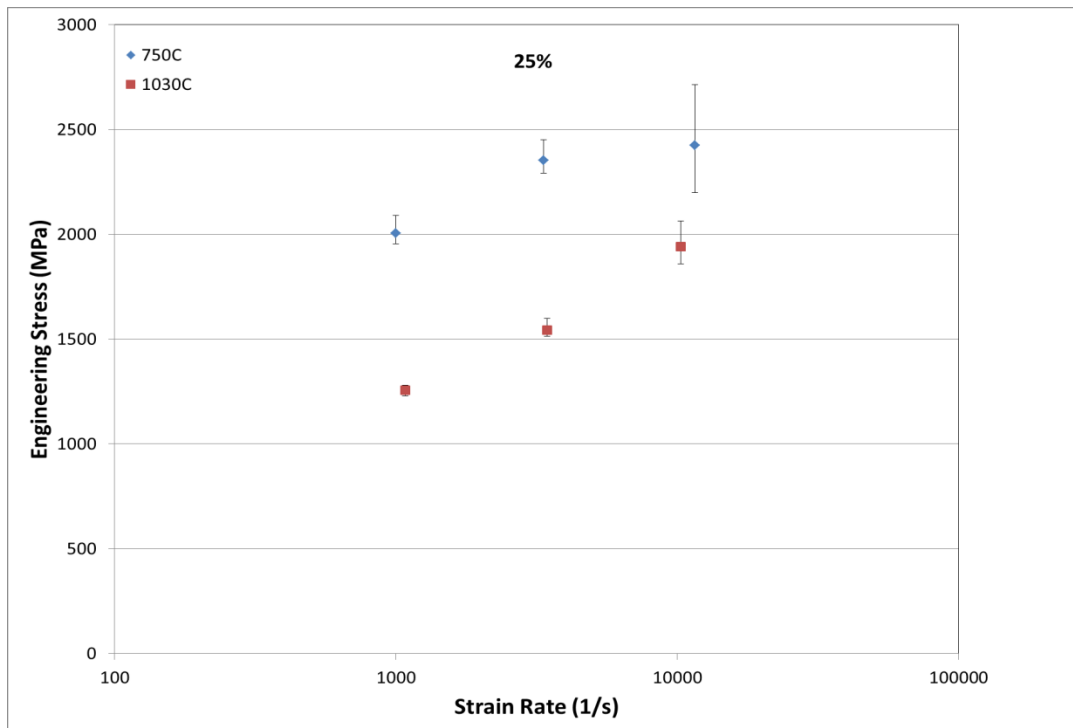
(a)



(b)



(c)



(d)

**Figure 34. Strain-rate and temperature effects at different strains  
(a) 5%; (b) 10%; (c) 20%; (d) 25%**

*This page intentionally left blank.*

## 4. CONCLUSIONS

The current high-temperature Kolsky compression bar technique was modified to enable high-strain-rate characterization of small disc-shaped iridium alloy specimens at high temperatures. The modifications included the new design of a sandwich structure consisting of two alumina platens with the iridium alloy specimen in between. This sandwich structure was heated separately before dynamic loading. The automated high-temperature Kolsky compression bar system removed the sandwich structure from the furnace and placed it in contact with the room-temperature incident and transmission bars just before dynamic loading of the specimen. This modification shortened the CCT, effectively maintaining a constant iridium alloy specimen temperature during testing and minimizing the temperature gradient in the pressure bars during dynamic loading. An uncertainty analysis showed that the effect of introducing the alumina platens on the resultant stress-strain response of the iridium alloy specimen was negligible.

All of these modifications and analyses enabled the generation of reliable high-rate high-temperature compressive stress-strain curves for the iridium alloy. The iridium alloy was dynamically characterized in compression at four different strain rates ranging from 300 to  $10000\text{ s}^{-1}$  at the temperatures of  $750^{\circ}\text{C}$  and  $1030^{\circ}\text{C}$ . The compressive stress-strain response of the iridium alloy in this study showed significant sensitivities to both strain rate and temperature. At a certain strain, the stress increased with increasing strain rate at any given temperature; whereas, the stress decreased with increasing temperature at any given strain rate. Obtaining these high-rate high-temperature compressive responses for the iridium alloy enables the development of reliable material models and model validation for safety analyses. The techniques developed in this study can be applied to high-rate high-temperature characterization of other thin-sheet materials.

*This page intentionally left blank.*

## 5. REFERENCES

1. Ohriner, E. K., *Processing of Iridium and Iridium Alloys, Methods from Purification to Fabrication*, Platinum Metals Review, 52:186-197 (1998).
2. Skrabek, E. A., *Consideration of Lower Allowable Impact Temperature for DOP26 Iridium Alloy Fueled Clads*, In: Proceedings of Space Technology and Applications International Forum – STAIF 2005, M. S. El-Genk (ed.), American Institute of Physics, pp. 776-781 (2005).
3. George, T. G., *High-strain-rate, High-temperature Biaxial Testing of DOP-26 Iridium*, Los Alamos National Laboratory Report, LA-11065, (1998).
4. Schneibel, J. H., Carmichael, C. A., George, E. P., *High Strain Rate Tensile Testing of DOP-26 Iridium*, Oak Ridge National Laboratory Report, ORNL/TM-2007/81 (2007).
5. Chen, W., Song, B., *Split Hopkinson (Kolsky) Bar, Design, Testing and Applications*, Springer New-York, (2011).
6. Seo, S., Min, O., Yang, H., *Constitutive Equation for Ti-6Al-4V at High Temperatures Measured Using the SHPB Technique*, International Journal of Impact Engineering, 31:735-754 (2005).
7. Frantz, C. E., Follansbee, P. S., Wright, W. T., *Experimental Techniques with the Split Hopkinson bar*. In: Proceedings of the 8<sup>th</sup> International Conference on High Energy Rate Fabrication, Texas, 229-236 (1984).
8. Lennon, A. M., Ramesh, K. T., *A Technique for Measuring the Dynamic Behavior of Materials at High Temperatures*. International Journal of Plasticity, 14:1279-1292 (1998).
9. Apostol, M., Vuoristo, T., Kuokkala, V. T., *High Temperature High Strain Rate Testing with a Compressive SHPB*. Journal de Physique IV, 110:459-464 (2003).
10. Song, B., Antoun, B. R., Boston, M., *Development of High-Temperature Kolsky Compression Bar Techniques for Recrystallization Investigation*. The European Physical Journal ST, 206:25-33 (2012).
11. Holman, J. P., *Heat Transfer*, Seventh Edition, McGraw-Hill, New York, NY, pg 140 (1990).
12. <http://www.segaerosol.com/>
13. Latella, B. A., Liu, T., *High-Temperature Young's Modulus of Alumina during Sintering*. Journal of American Ceramic Society, 88:773-776 (2005).
14. Safa, K., Gary, G., *Displacement Correction for Punching at a Dynamically Loaded Bar End*. International Journal of Impact Engineering, 37:371-384 (2010).
15. Pan, Y., Chen, W., Song, B., *The Upper Limit of Constant Strain Rate in a Split Hopkinson Pressure Experiment*. Experimental Mechanics, 45:440-446 (2005).
16. Song, B., Chen, W., Antoun, B. R., Frew, D. J., *Flow Stress Obtained on Ductile Specimens Deforming at High Strain Rates*. Experimental Mechanics, 47:671-679 (2007).

*This page intentionally left blank.*

## APPENDIX A: SUMMARY OF DYNAMIC TESTING CONDITIONS OF INDIVIDUAL SAMPLES

A summary of dynamic testing conditions including testing temperature, strain rate, and date, for each individual sample is tabulated in Table 3.

**Table 3. Dynamic testing conditions of samples**

| <b>Specimen No.</b> | <b>Testing Temperature (°C)</b> | <b>Strain Rate (1/s)</b> | <b>Testing Date</b> |
|---------------------|---------------------------------|--------------------------|---------------------|
| 6                   | 750                             | 3350                     | 10/16/2012          |
| 7                   | 750                             | 3300                     | 10/17/2012          |
| 8                   | 750                             | 3400                     | 10/18/2012          |
| 12                  | 750                             | 950                      | 10/25/2012          |
| 14                  | 750                             | 1050                     | 10/31/2012          |
| 16                  | 750                             | 1000                     | 10/31/2012          |
| 20                  | 750                             | 450                      | 11/05/2012          |
| 21                  | 750                             | 380                      | 11/06/2012          |
| 22                  | 750                             | 420                      | 11/06/2012          |
| 23                  | 750                             | 13000                    | 11/09/2012          |
| 25                  | 750                             | 11300                    | 11/09/2012          |
| 26                  | 750                             | 10900                    | 11/09/2012          |
| 28                  | 750                             | 1000                     | 11/13/2012          |
| 29                  | 750                             | 11000                    | 12/18/2012          |
| 31                  | 1030                            | 3400                     | 01/09/2013          |
| 32                  | 1030                            | 3500                     | 01/10/2013          |
| 33                  | 1030                            | 3450                     | 01/10/2013          |
| 35                  | 1030                            | 1100                     | 01/24/2013          |
| 36                  | 1030                            | 1050                     | 01/25/2013          |
| 37                  | 1030                            | 1100                     | 01/25/2013          |
| 38                  | 1030                            | 350                      | 01/28/2013          |
| 39                  | 1030                            | 330                      | 01/28/2013          |
| 40                  | 1030                            | 340                      | 01/28/2013          |
| 42                  | 1030                            | 10500                    | 01/29/2013          |
| 43                  | 1030                            | 10300                    | 01/29/2013          |
| 45                  | 1030                            | 10300                    | 01/30/2013          |
| 46                  | 1030                            | 10200                    | 01/30/2013          |

*This page intentionally left blank.*

## DISTRIBUTION

1 US Department of Energy, NE-75  
Office of Radioisotope Power Systems  
Attn: Ryan D. Bechtel, (2)  
19901 Germantown Road  
Germantown, MD 20874

2 Tetra Tech, Inc.  
Attn: Steven Giannino (2)  
20251 Century Boulevard, Suite 200  
Germantown, MD 20874-7114

1 Johns Hopkins University, 1E-255  
Attn: Yale Chang (1)  
Applied Physics Laboratory  
11100 Johns Hopkins Road  
Laurel, MD 20723

2 Oak Ridge National Laboratory  
Attn: G. B. Ulrich (2)  
P.O. Box 2008  
Oak Ridge, TN 37831-6079

1 Oak Ridge National Laboratory  
Attn: E. P. George (1)  
P.O. Box 2008  
Oak Ridge, TN 37831-6115

|   |        |               |           |
|---|--------|---------------|-----------|
| 1 | MS0557 | D. Croessmann | Org. 1520 |
| 1 | MS0557 | D. Jones      | Org. 1558 |
| 2 | MS0557 | B. Song       | Org. 1558 |
| 1 | MS0744 | J. Bignell    | Org. 6233 |
| 2 | MS0747 | R. Lipinski   | Org. 6223 |
| 1 | MS0815 | J. Johannes   | Org. 1500 |
| 1 | MS0840 | J. Redmond    | Org. 1550 |
| 1 | MS9014 | C. Moen       | Org. 8238 |
| 1 | MS9042 | J. Ostien     | Org. 8256 |
| 1 | MS9409 | K. Nelson     | Org. 8256 |

|   |        |                   |                        |
|---|--------|-------------------|------------------------|
| 1 | MS0899 | Technical Library | 9536 (electronic copy) |
|---|--------|-------------------|------------------------|



