REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY): 02-08-2022

2. REPORT TYPE: Final Report

3. DATES COVERED (From - To): 4-May-2017 - 3-Jan-2022

4. TITLE AND SUBTITLE: Final Report: Damage and Temperature around a Propagating Dynamic Crack

5a. CONTRACT NUMBER: W911NF-17-1-0241

5b. GRANT NUMBER:

5c. PROGRAM ELEMENT NUMBER: 611102

5d. PROJECT NUMBER:

5e. TASK NUMBER:

5f. WORK UNIT NUMBER:

6. AUTHORS:

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

Purdue University
Sponsored Program Services
155 S Grant Street
West Lafayette, IN 47907 -2114

8. PERFORMING ORGANIZATION REPORT NUMBER:

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S): ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S): 70794-EG.7

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Weinong Chen
					19b. TELEPHONE NUMBER 765-494-1788

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 30-Dec-2022

Agency Code: 21XD

Proposal Number: 70794EG **Agreement Number: W911NF-17-1-0241**

INVESTIGATOR(S):

Name: Weinong Chen Ph.D.
Email: wchen@purdue.edu
Phone Number: 7654941788
Principal: Y

Organization: **Purdue University**
Address: Sponsored Program Services, West Lafayette, IN 479072114
Country: USA
DUNS Number: 072051394 EIN: 356002041

Report Date: 03-Apr-2022 Date Received: 02-Aug-2022
Final Report for Period Beginning 04-May-2017 and Ending 03-Jan-2022
Title: Damage and Temperature around a Propagating Dynamic Crack
Begin Performance Period: 04-May-2017 **End Performance Period:** 03-Jan-2022
Report Term: 0-Other
Submitted By: Weinong Chen Email: wchen@purdue.edu
Phone: (765) 494-1788
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: **STEM Participants:**

Major Goals: During high-rate deformation, due to material heterogeneity and stress-wave interactions, the deformation distribution inside a material may be very localized, leading to localized temperature rise and localized damage that lead to eventual failure of the material. In order to understand such microstructure and loading-rate dependent damage evolution inside materials, it is desired to experimentally measure the microstructure evolution and the associated temperature field evolution during high-rate deformation. In this study, we aim to capture the rapid evolution of damage and temperature fields ahead of a dynamically propagating crack or shear-band tip in real-time. The loading rates are varied over a wide range using a Kolsky bar and a light gas gun impacting the specimen at various velocities. Since microstructural evolutions are not visible from the surfaces of most materials, a high-speed, high-resolution X-ray visualization method (synchrotron X-ray high-speed phase contrast imaging at up to 5 million frames per second) is employed to capture the microstructure and dynamic damage evolution ahead of the crack or shear-band tip inside opaque materials. The observation window of the synchrotron X-ray is limited to about 1.5 by 2 mm, the crack/shear band tip area is selected to ensure that severe deformation and damage processes are visualized. There are no commercially available high-speed thermal cameras that are capable to capture the rapid temperature changes in a dynamically deforming material, we developed a new two-dimensional topographical temperature measurement method using laser-induced phosphorescence particles, either embedded inside composite and polymer material specimens or coated on the surfaces of metallic specimens, to provide continuous temperature measurements at frame rates in the order of a million frames per second. This frame rate is an order of magnitude higher than any thermal camera in the market, to capture the rapidly changing full-field temperature field evolution. The specimen materials started with metals (two aluminum alloys) and have been expanded to two polymers (Sylgard and epoxy), which allow the examination of the effects of specimen thermal-mechanical behavior in stress-concentrated areas in the specimens. The results from these experiments provide an improved fundamental understanding on the conditions that lead to dynamic crack or shear-band propagation and the associated energy dissipation mechanisms as functions of loading rates, as well as the innovative dynamic experimental methods.

Accomplishments: To characterize localized microstructure evolution with associated localized temperature rise that lead to eventual failure of the material, we utilized a high-speed X-ray imaging system to focus the observation window on a pre-designed deformation location (shear band) that enabled us to visualize the dynamic deformation localization in real time. We used a commercial high-speed infrared camera to capture the rapid surface temperature distribution evolution in aluminum samples. To further increase the frame rate of the thermo imaging, we also developed a high-speed laser phosphorescence method. More recently, we have combined high-speed X-ray phase contract imaging (PCI), high-speed X-ray diffraction, and high-speed thermal imaging in one impact experiment to set the stage for future research aiming to reveal the inter connections among the material deformation, microstructure evolution, and temperature variation in the material under impact loading.

The main experimental setup used in this research is a Kolsky bar setup integrated with high-speed synchrotron X-ray imaging and thermal imaging. A shear-localization sample geometry is designed, with the X-ray imaging and thermal imaging focused on shear localization area. A Kolsky bar set up is used to apply controlled impact load on the “top-hat” shear sample that promotes shear localization. To “see” through the opaque sample, the lighting source in high-speed imaging is replaced by the synchrotron X-ray source available at Beamline 32 ID-B of the Advanced Photon Source (APS) at Argonne National Laboratory. The X-ray source enables high-speed X-ray phase contract imaging, which was developed at 32 ID-B.

In this study, we examined aluminum 7075-T6 and 6061-T6 hat-shaped specimens under dynamic shear loading provided by a Kolsky bar at an impact speed of ~16 m/s. The experiments on aluminum samples revealed that both materials displayed the trend of uniform shear deformation, formation of shear bands, cracking and then shear failure. 6061-T6 has a more ductile behavior under the dynamic shear loading and requires larger strain to form an adiabatic shear band.

A commercially available Telops high-speed infrared thermal camera was used to capture the rapid temperature field evolution associated with the shear banding . A series of high-speed thermal images recorded the full-field dynamic temperature evolution process at the top speed of any infrared high-speed thermal cameras available in the market today (70,000 frames per second with still a recognizable thermal field). The sample material was Aluminum 6061-T6. Such series of thermal images were taken from repeated experiments in samples made of both 6061-T6 and 7075-T6.

By assuming the emissivity to be 0.15, the maximum temperature during the loading was found to be 720 K for 7075-T6 and 770 K for 6061-T6. This heat accumulation and the corresponding thermal instability during dynamic loading were found to be closely related to the formation of the adiabatic shear bands. Both X-ray and thermal imaging obtained in this set of experiments provides insightful information in determining the shear band width and tip location. From the images, the shear band width is estimated to be 20-50 μm for 7075-T6 and 30-70 μm for 6061-T6. Cracks initiate after the formation of shear bands. These cracks propagate in the same tracks as the shear bands at the velocity of approximately 1100 m/s. This was the first time when high-speed thermal images provided such detailed information on the dynamic deformation localization in a material subjected to impact loading. When these results were published, the journal Experimental Mechanics selected this article as the cover story of the issue.

Even though the results of the temperature field measurement were well received, the limitations of spatial and temporal resolution of infrared techniques, especially the 70,000 frames-per-second upper limit in imaging rate, prevented the capture of rapidly evolving temperature field with sufficient resolution. To overcome the frame-rate limit such that we can take thermal images at hundreds of thousands of images per second, we invested significant amount of effort developing a high-speed laser phosphorescence method. Using this method, the spatial resolution is no longer limited by the infrared wavelength, but solely depends on the high-speed optical camera, which can easily reach kHz or even MHz frame rate with current technology. We encountered a series of unexpected technical challenges in this endeavor, which is still under research and development.

There are two primary types of phosphors that can be excited by laser and serve as distributed sensors to determine the local and full-field rapid temperature variation histories. One type is where the local temperature is related to the decay time of light immitted by the phosphors. However, from our trial experiments, we observed that over the decaying time, the sample under dynamic loading may have physically moved, leading to poor spatial resolution of the temperature measurements. In the second type of phosphors, the manifestation of local temperature is in the ratio of emitting light intensities over different wave lengths of the spectrum, making the measurement instant and significantly improve the spatial resolution. Figure 4 in the attachment illustrates the working principle of the second type of thermal phosphors where the ratio of emitting light intensities over different wave lengths, as indicated by the black dashed-lined boxes, of the spectrum reveals the local temperature. The signal strength remained consistent over the high-frequency range, but varied significantly in the low-frequency window as local temperature varied. The ratio of the signal strengths over the two frequency ranges, after calibration, gives the local temperature of the phosphor.

We applied this ratio method to measure the rapid temperature rise in Sylgard sample under impact. Unexpectedly, the Sylgard did not demonstrate a sufficiently high temperature rise to be clearly recognizable in the phosphor light detection. All the temperature measured over 40 experiments was around room temperature. These temperature measurements by the thermal phosphors were sampled at 1 MHz frame rate, which is an order of magnitude higher than the highest frame rate offered by any commercial high-speed thermal camera available in the market.

To calibrate the temperature field, we used the same infrared high-speed camera to measure the dynamic temperature field on the Sylgard samples. The camera frame rate may not be high enough to capture the rise phase of the temperature on the sample. However, once the temperature is raised by stress-wave loading, the decay time through diffusion is much longer. The thermal camera will be able to capture the temperature field before it decays down. To increase the temperature in the sample, we used a gas-gun to impact the Sylgard samples at velocities an order of magnitude higher (~160 m/s). The results also showed that there were only a few degrees' temperature rise in the Sylgard. We are now employing a second calibration method, but the time frame will be beyond this program, to further confirm the magnitude of the temperature rise.

In the meanwhile, we have combined high-speed X-ray phase contract imaging (PCI), high-speed X-ray diffraction, and high-speed thermal imaging in one impact experiment to set the stage for future research aiming to reveal the inter connections among the material deformation, microstructure evolution, and temperature variation in the material under impact loading. We will be able to obtain the measurements in deformation, microstructure evolution, and temperature field evolution simultaneously, which is an unprecedented capability.

Training Opportunities: The program provided graduate students opportunities to learn and develop different experimental methods, as well as collaboration between two research groups (Chen group and Meyer group) at Purdue University, as well as with a group outside Purdue: Professor Amy Clarke’s group at Colorado School of Mines.

Results Dissemination: 3 Journal Articles.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Weinong Wayne Chen
Person Months Worked: 1.00
Funding Support:
Project Contribution:
National Academy Member: N

Participant Type: Co-Investigator
Participant: Terrence Meyer
Person Months Worked: 1.00
Funding Support:
Project Contribution:
National Academy Member: N

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Composite Materials
Publication Identifier Type: DOI Publication Identifier: 10.1177/0021998318797394
Volume: 52 Issue: 25 First Page #: 3539
Date Submitted: 8/31/19 12:00AM Date Published: 9/1/18 4:00AM
Publication Location:
Article Title: Dynamic crack propagation from a circular defect in a unidirectional carbon fiber reinforced plastic composite
Authors: Yizhou Nie, Niranjan D Parab, Jou-Mei Chu, Garam Kim, Tao Sun, Kamel Fezzaa, Ronald Sterkenburg,
Keywords: Carbon fiber reinforced plastic, crack initiation, dynamic behaviors, X-ray phase contrast imaging
Abstract: A single-ply unidirectional IM7/8552 carbon fiber reinforced plastic composite with artificially introduced circular defects is subjected to dynamic tensile loading using a modified Kolsky tension bar. A high-speed X-ray phase contrast imaging method is integrated with the Kolsky bar setup to record the crack initiation from the defects and subsequent propagation in the material in real time during the tensile loading. The tensile loading was applied either in longitudinal or transverse direction of the specimens. Shear failure of the matrix and axial splitting along the loading/fiber direction were observed in longitudinal specimens to initiate from the edge of the artificial circular defects. Debonding of fiber and matrix was observed in transverse specimens, which initiated from the top and bottom edge of the hole. The dynamic tensile loading history during the crack propagation was recorded using a piezoelectric load cell and synchronized with the obs
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Acta Biomaterialia
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.actbio.2019.03.045
Volume: 90 Issue: First Page #: 278
Date Submitted: 8/31/19 12:00AM Date Published: 5/1/19 4:00AM
Publication Location:
Article Title: High-speed X-ray visualization of dynamic crack initiation and propagation in bone
Authors: Xuedong Zhai, Zherui Guo, Jinling Gao, Nesredin Kedir, Yizhou Nie, Ben Claus, Tao Sun, Xianghui Xiac
Keywords: Bone; High-rate loadings; High-speed X-ray phase contrast imaging; Kolsky bars; Dynamic fracture toughness
Abstract: An understanding of the crack-growth resistance in bone at high loading rates is essential for the prediction of fracture risk under blast and impact loadings. In the present study, the propagation of physiologically cracks in pig cortical and cancellous bone at a high loading rate was observed using high-speed synchrotron X-ray phase-contrast imaging (PCI) to identify the toughness mechanism under dynamic fractures. A modified Kolsky compression bar was used to apply dynamic three-point flexural loadings on notched specimens and images of fractures were recorded using a synchronized high-speed synchrotron X-ray imaging set-up. Three-dimensional synchrotron X-ray tomography was conducted to examine the microstructure of the bone before high loading-rate experiments. Fracture deflections, a prime toughening mechanism in bone at low rates, were observed in cortical bone at high rate in this study.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Experimental Mechanics
Publication Identifier Type: DOI Publication Identifier: 10.1007/s11340-019-00518-y
Volume: 59 Issue: 5 First Page #: 669
Date Submitted: 8/31/19 12:00AM Date Published: 4/1/19 4:00AM
Publication Location:
Article Title: A Microscopic Experimental Method Transversely Loading on Single High-Performance Fibers
Authors: J. Gao, Y. Nie, B.H. Lim, N. Kedir, W. Chen
Keywords: Transverse loading, single fiber, uncoated fiber, failure process, SEM
Abstract: We developed a microscopic experimental method that transversely loads and images single high-performance fibers. The experimental set-up was inside the chamber of a scanning electron microscope (SEM). Force and displacement histories were recorded by the loading device. The SEM enabled in-situ observation of the fiber's initial contact with the transverse indenter and subsequent deformation, crack initiation and propagation until the final failure. Within the loading device, fiber gauge length, indenter tip radius and loading direction can be varied as desired. To demonstrate the new experimental capability, initial results for a razor blade transversely cutting a Dyneema® SK76 fiber are presented in this paper. To avoid the effect from the conductive coating on the mechanical behavior of the fiber, a low vacuum detector was adopted to capture the deformation and failure of an uncoated fiber. These experiments revealed the damage and failure processes of single fibers.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of the Mechanics and Physics of Solids
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.jmps.2019.07.010
Volume: 131 Issue: First Page #: 358
Date Submitted: 8/31/19 12:00AM Date Published: 10/1/19 4:00AM
Publication Location:
Article Title: Real-time visualization of dynamic fractures in porcine bones and the loading-rate effect on their fracture toughness
Authors: Xuedong Zhai, Jinling Gao, Yizhou Nie, Zherui Guo, Nesredin Kedir, Ben Claus, Tao Sun, Kamel Fezza
Keywords: Cortical bone; Trabecular bone; Nasal bone; Fracture behavior; High-speed X-ray phase contrast imaging; Loading rate
Abstract: We visualized, in real time, the dynamic fracture behaviors in porcine cortical bone from humerus and porcine trabecular bone from nasal bone at a high loading rate using high-speed synchrotron X-ray phase-contrast imaging (PCI). Dynamic three-point bending loading was applied on notched bone specimens by a modified Kolsky compression bar and images of the entire fracture events were recorded with an ultra-high-speed camera. Experiments at a quasi-static loading rate on material testing system (MTS) were also performed to identify the loading-rate effects on the fracture toughness of the two types of bone. Three-dimensional synchrotron X-ray computed tomography was conducted to examine the initial microstructures in the bone specimens before mechanical loading. At the dynamic loading rate, the onset locations of crack initiation were found to be independent from the bone types. The deleterious effect of dynamic loading rate on bone's fracture toughness was verified in this study.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 30-Dec-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of the Mechanical Behavior of Biomedical Materials
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.jmbbm.2019.103597
Volume: 103 Issue: First Page #: 103597
Date Submitted: Date Published: 3/1/20 5:00AM
Publication Location:
Article Title: The effects of loading-direction and strain-rate on the mechanical behaviors of human frontal skull bone
Authors: Xuedong Zhai, Eric A. Nauman, Dana Moryl, Roy Lycke, Weinong W. Chen
Keywords: Human cranial bone; Mechanical property; Stress-strain; Anisotropy; Strain rate
Abstract: Most fatal human skull injuries occur under impact loading conditions, such as car collisions, where the strain rates fall in the range of intermediate (1/s?102/s) and high (102/s?103/s) rates. Therefore, knowledge of the mechanical behaviors of human cranial bone at higher strain rates, i.e., intermediate and high strain rates, may provide insight into the prevention of skull injuries and help the design of efficient head protection systems. In the present study, the compressive mechanical behaviors of human frontal skull bone along and perpendicular to its through-the-thickness direction were experimentally characterized at quasi-static (0.01/s), intermediate (30/s) and high (625/s) strain rates in this study. A total number of 75 specimens prepared from three male donors with ages of 70-74 were separated into three groups: quasi-static (N=23), intermediate (N=23), and high (N=29) strain rates.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Partners

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I certify that the information in the report is complete and accurate:
Signature: Weinong Chen
Signature Date: 8/2/22 5:39PM

Research Performance Progress Report (RPPR)

Distribution Statement

- DISTRIBUTION A. Approved for public release: distribution unlimited.

Accomplishments

What were the major goals and objectives of the project?

During high-rate deformation, due to material heterogeneity and stress-wave interactions, the deformation distribution inside a material may be very localized, leading to localized temperature rise and localized damage that lead to eventual failure of the material. In order to understand such microstructure and loading-rate dependent damage evolution inside materials, it is desired to experimentally measure the microstructure evolution and the associated temperature field evolution during high-rate deformation. In this study, we aim to capture the rapid evolution of damage and temperature fields ahead of a dynamically propagating crack or shear-band tip in real-time. The loading rates are varied over a wide range using a Kolsky bar and a light gas gun impacting the specimen at various velocities. Since microstructural evolutions are not visible from the surfaces of most materials, a high-speed, high-resolution X-ray visualization method (synchrotron X-ray high-speed phase contrast imaging at up to 5 million frames per second) is employed to capture the microstructure and dynamic damage evolution ahead of the crack or shear-band tip inside opaque materials. The observation window of the synchrotron X-ray is limited to about 1.5 by 2 mm, the crack/shear band tip area is selected to ensure that severe deformation and damage processes are visualized. There are no commercially available high-speed thermal cameras that are capable to capture the rapid temperature changes in a dynamically deforming material, we developed a new two-dimensional topographical temperature measurement method using laser-induced phosphorescence particles, either embedded inside composite and polymer material specimens or coated on the surfaces of metallic specimens, to provide continuous temperature measurements at frame rates in the order of a million frames per second. This frame rate is an order of magnitude higher than any thermal camera in the market, to capture the rapidly changing full-field temperature field evolution. The specimen materials started with metals (two aluminum alloys) and have been expanded to two polymers (Sylgard and epoxy), which allow the examination of the effects of specimen thermal-mechanical behavior in stress-concentrated areas in the specimens. The results from these experiments provide an improved fundamental understanding on the conditions that lead to dynamic crack or shear-band propagation and the associated energy dissipation mechanisms as functions of loading rates, as well as the innovative dynamic experimental methods.

What was accomplished towards achieving these goals?

To characterize localized microstructure evolution with associated localized temperature rise that lead to eventual failure of the material, we utilized a high-speed X-ray imaging system to focus the observation window on a pre-designed deformation location (shear band) that enabled us to visualize the dynamic deformation localization in real time. We used a commercial high-speed infrared camera to capture the rapid surface temperature distribution evolution in aluminum samples. To further increase the frame rate of the thermo imaging, we also developed a high-speed laser phosphorescence method. More recently, we have combined high-speed X-ray phase contract imaging (PCI), high-speed X-ray diffraction, and high-speed thermal imaging in one impact experiment to set the stage for future research aiming to reveal the inter connections among the material deformation, microstructure evolution, and temperature variation in the material under impact loading.

The main experimental setup used in this research project is schematically shown in Fig. 1. On the left side, a shear-localization sample geometry is present. The blue window is where X-ray imaging and thermal imaging are focused on. A Kolsky bar set up (on the right) is used to apply controlled impact load on the “top-hat” sample that promotes shear localization. To “see” through the opaque sample, the lighting source in high-speed imaging is replaced by the synchrotron X-ray source available at Beamline 32 ID-B of the Advanced Photon Source (APS) at Argonne National Laboratory. The X-ray source enables high-speed X-ray phase contract imaging, which was developed at 32 ID-B.

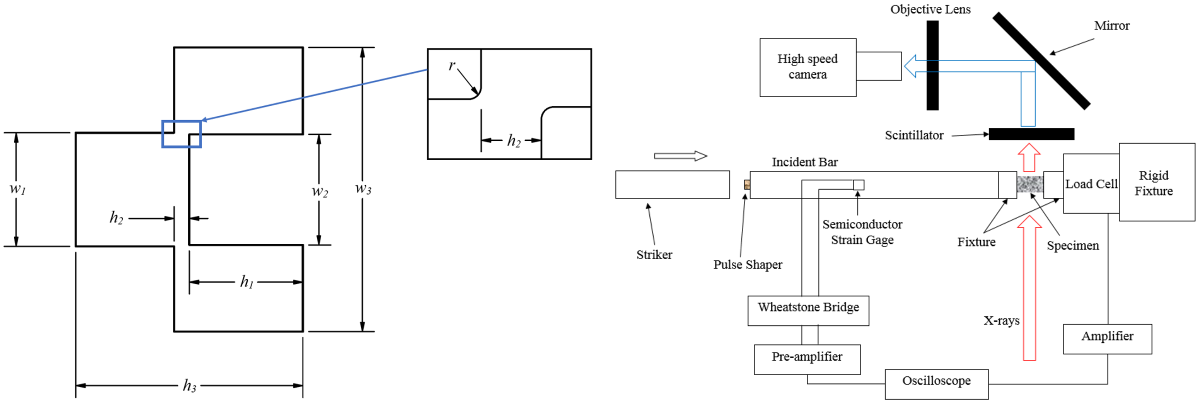
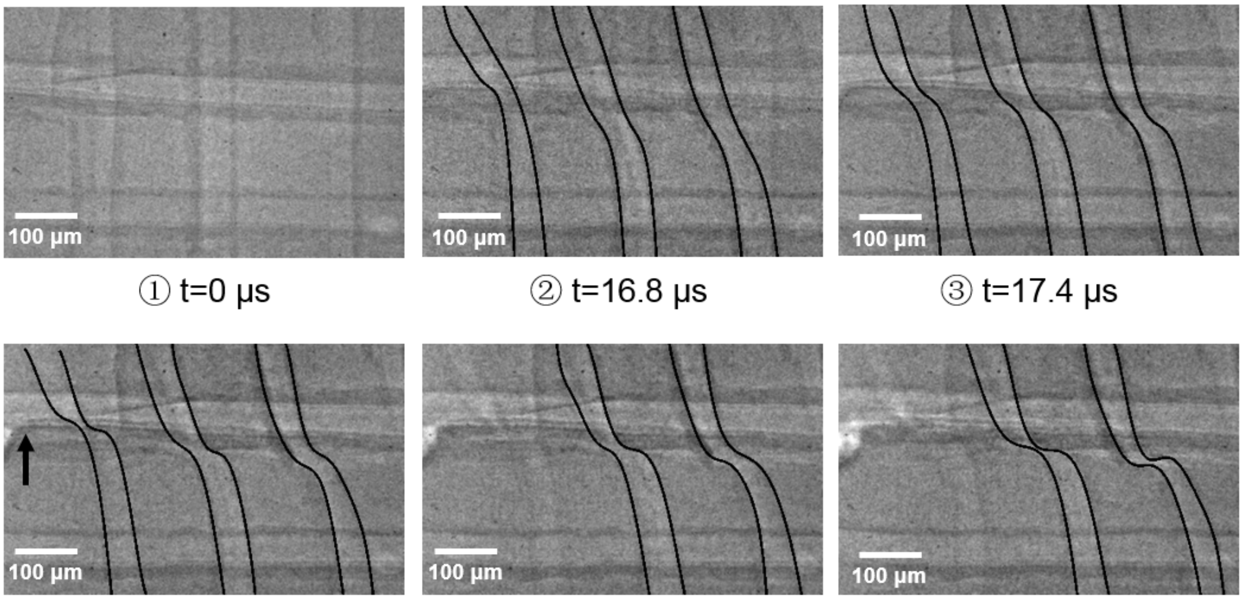


Figure 1: Shear localization sample geometry and Kolsky bar set up with X-ray imaging.

Figure 2 shows a time-series of images that record the shear localization process within the intended shear zone in an aluminum sample, which review the dynamic shear band formation process. In this study, we examined aluminum 7075-T6 and 6061-T6 hat-shaped specimens under dynamic shear loading provided by a Kolsky bar at an impact speed of ~16 m/s. Our research group has used this experimental setup and the X-ray source to visualize the dynamic deformation and damage evolution inside many opaque materials in recent years.

The experiments on aluminum samples revealed that both materials displayed the trend of uniform shear deformation, formation of shear bands, cracking and then shear failure. 6061-T6 has a more ductile behavior under the dynamic shear loading and requires larger strain to form an adiabatic shear band.



① t=0 μs ② t=16.8 μs ③ t=17.4 μs

④ t=18 μs ⑤ t=18.6 μs ⑥ t=19.2 μs

Figure 2: Deformation field evolution within the localized zone in the shear-localization sample.

A commercially available Telops high-speed infrared thermal camera was used to capture the rapid temperature field evolution associated with the shear banding showing in Fig. 2. Figure 3 shows a series of high-speed thermal images that record the full-field dynamic temperature evolution process at the top speed of any infrared high-speed thermal cameras available in the market today (70,000 frames per second with still a recognizable thermal field). The sample material was Aluminum 6061-T6. Such series of thermal images were taken from repeated experiments in samples made of both 6061-T6 and 7075-T6.

By assuming the emissivity to be 0.15, the maximum temperature during the loading was found to be 720 K for 7075-T6 and 770 K for 6061-T6. This heat accumulation and the corresponding thermal instability during dynamic loading were found to be closely related to the formation of the adiabatic shear bands. Both X-ray and thermal imaging obtained in this set of experiments provides insightful information in determining the shear band width and tip location. From the images, the shear band width is estimated to be 20-50 μm for 7075-T6 and 30-70 μm for 6061-T6. Cracks initiate after the formation of shear bands. These cracks propagate in the same tracks as the shear bands at the velocity of approximately 1100 m/s. This was the first time when high-speed thermal images provided such detailed information on the dynamic deformation localization in a material subjected to impact loading. When these results were published, the journal *Experimental Mechanics* selected this article as the cover story of the issue.

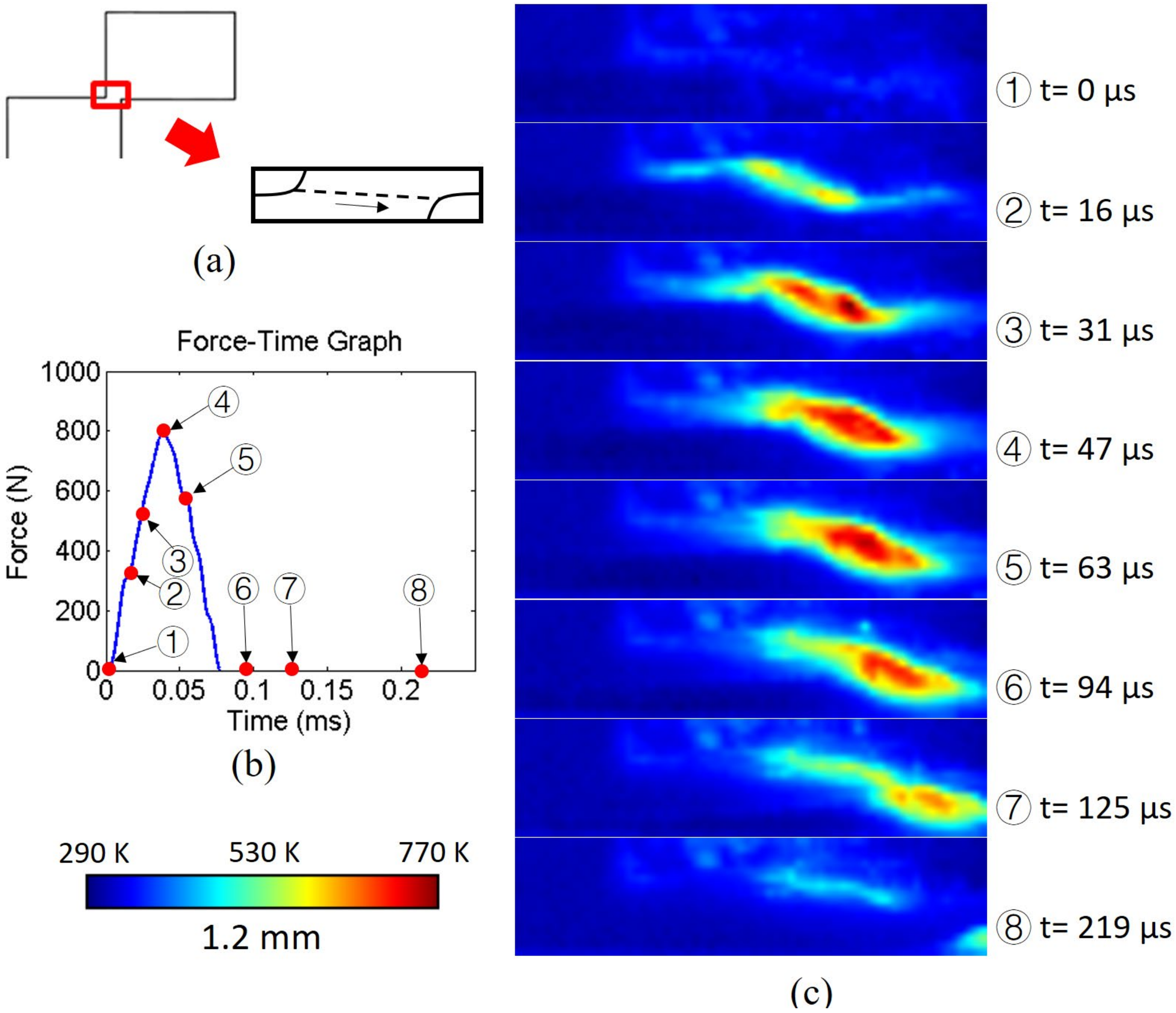
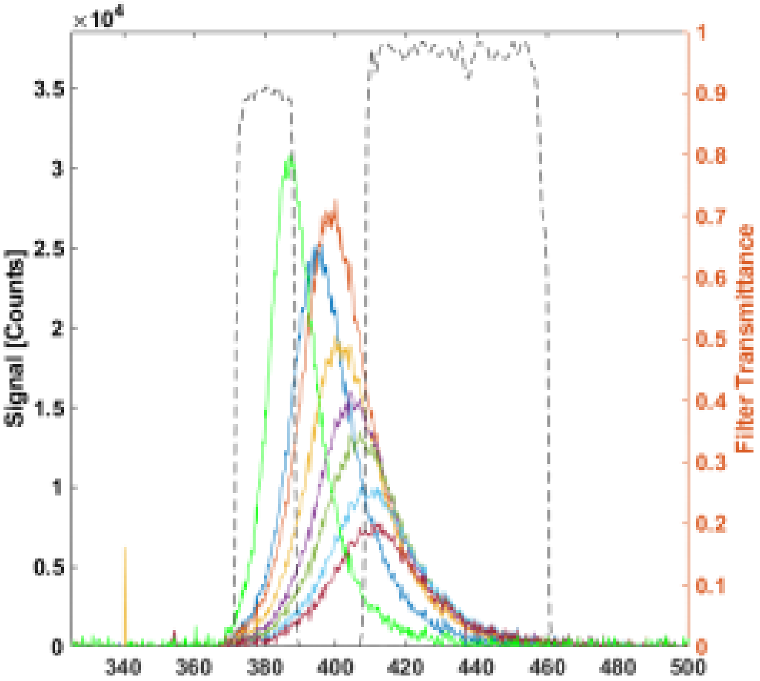


Figure 3: High-speed images of the evolution of full-field temperature distribution over the sample. (a) Region of imaging on the sample (localized shear deformation zone); (b) Thermal imaging time indicated on the time history of load on the sample; and (c) Recorded dynamic temperature field evolution that shows a peak temperature of about 770K.

Even though the results of the temperature field measurement were well received, the limitations of spatial and temporal resolution of infrared techniques, especially the 70,000 frames-per-second upper limit in imaging rate, prevented the capture of rapidly evolving temperature field with sufficient resolution. To overcome the frame-rate limit such that we can take thermal images at hundreds of thousands of images per second, we invested significant amount of effort developing a high-speed laser phosphorescence method. Using this method, the spatial resolution is no longer limited by the infrared wavelength, but solely depends on the high-speed optical camera, which can easily reach kHz or even MHz frame rate with current technology. We encountered a series of unexpected technical challenges in this endeavor, which is still under research and development.

There are two primary types of phosphors that can be excited by laser and serve as distributed sensors to determine the local and full-field rapid temperature variation histories. One type is where the local temperature is related to the decay time of light immitted by the phosphors. However, from our trial experiments, we observed that over the decaying time, the sample under dynamic loading may have physically moved, leading to poor spatial resolution of the temperature measurements. In the second type of phosphors, the manifestation of local temperature is in the ratio of emitting light intensities over different wave lengths of the spectrum, making the measurement instant and significantly improve the spatial resolution. Figure 4 illustrates the working principle of the second type of thermal phosphors where the ratio of emitting light intensities over different wave lengths, as indicated by the black dashed-lined boxes, of the spectrum reveals the local temperature. The signal strength remained consistent over the high-frequency range, but varied significantly in the low-frequency window as local temperature varied. The ratio of the signal strengths over the two frequency ranges, after calibration, gives the local temperature of the phosphor.



Moore, 2021

Figure 4: Local temperature revealed by the signal strength ratio over two frequency regions (in black dashed boxes) in the spectrum of the light immitted by the thermal phosphor.

We initially explored the second type of phosphors by bonding them on the surface of the aluminum samples, but realized that the adhesive was not sufficiently strong to prevent the phosphors from jumping off the surface when stress waves pass. We then embedded them inside a Sylgard polymer, which is a common binder material in explosives (PBX), and subjected the phosphor-embedded samples (with and without a notch) to a compression Kolsky bar loading.

One side of the sample is exposed to laser illumination to measure the rapid temperature field evolution. The other side is painted with random patterns for strain field evolution measurements using digital imaging correlation (DIC). In this way the temperature field and strain field in the sample may be correlated in real time under impact loading. Figure 5 is a schematic of the experimental setup where one side of the sample reveals the temperature field evolution, whereas the other side shows the corresponding dynamic strain field evolution through digital imaging correlation (DIC). The dynamic load is supplied by a compression Kolsky bar. The sample has an axial slit at the edge of a circular hole to provide stress concentration to generate localized high temperatures, which is shown in Figure 6.

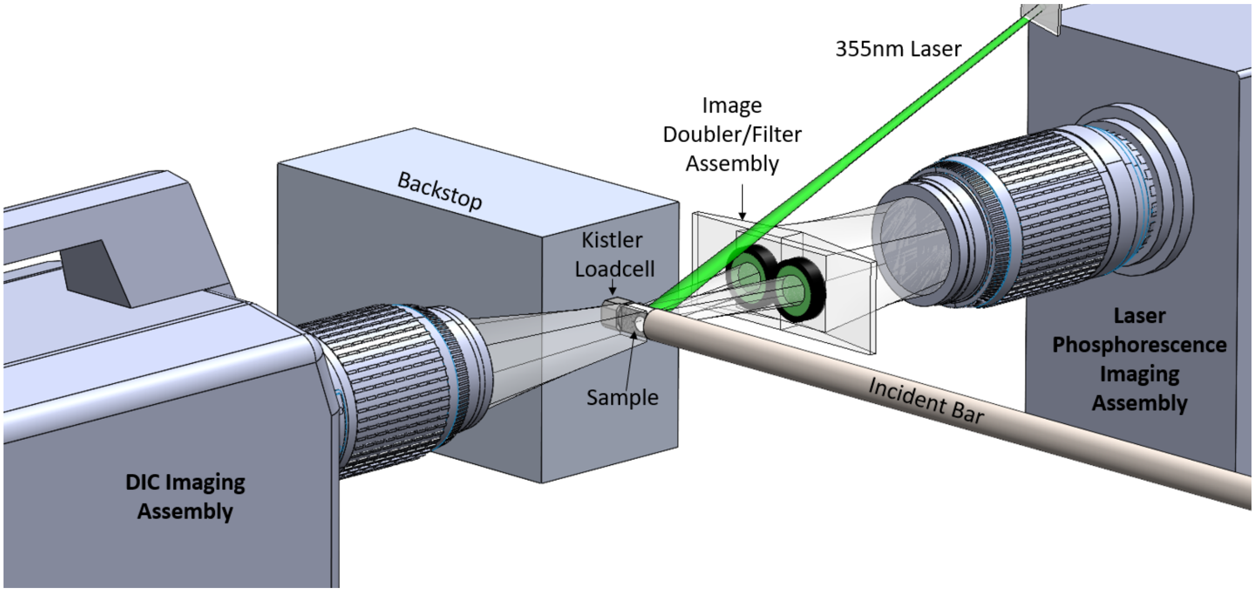


Figure 5: A schematic illustration of the experimental setup for dynamic temperature and strain fields measurements loaded by a compression Kolsky bar.

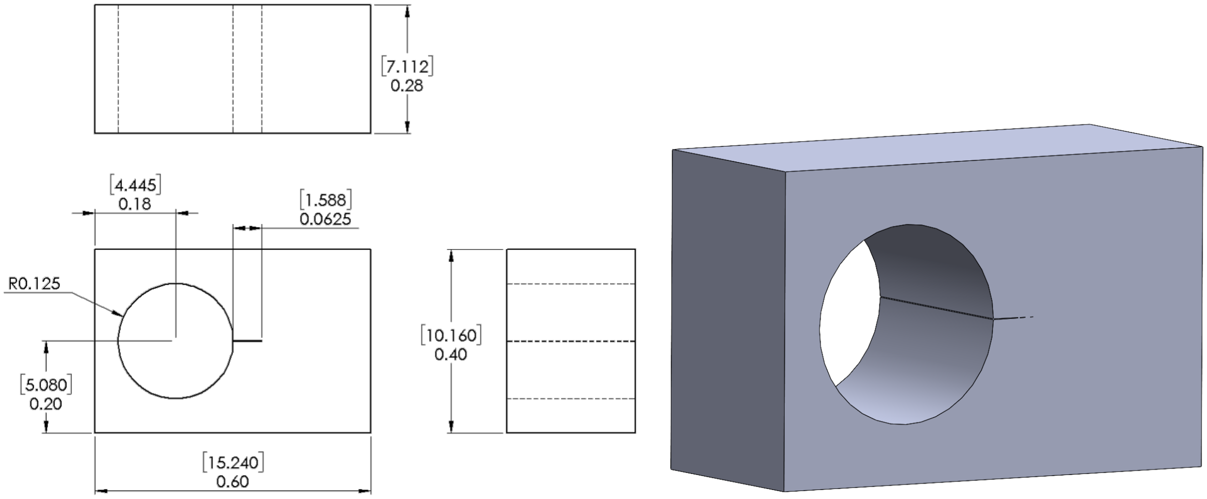


Figure 6: Sylgard specimen geometry for temperature and strain field measurements.

Unexpectedly, the Sylgard did not demonstrate a sufficiently high temperature rise to be clearly recognizable in the phosphor light detection. As shown in Figure 7, all the temperature measured over 40 experiments was around room temperature. These temperature measurements by the thermal phosphors were sampled at 1 MHz frame rate, which is an order of magnitude higher than the highest frame rate offered by any commercial high-speed thermal camera available in the market.

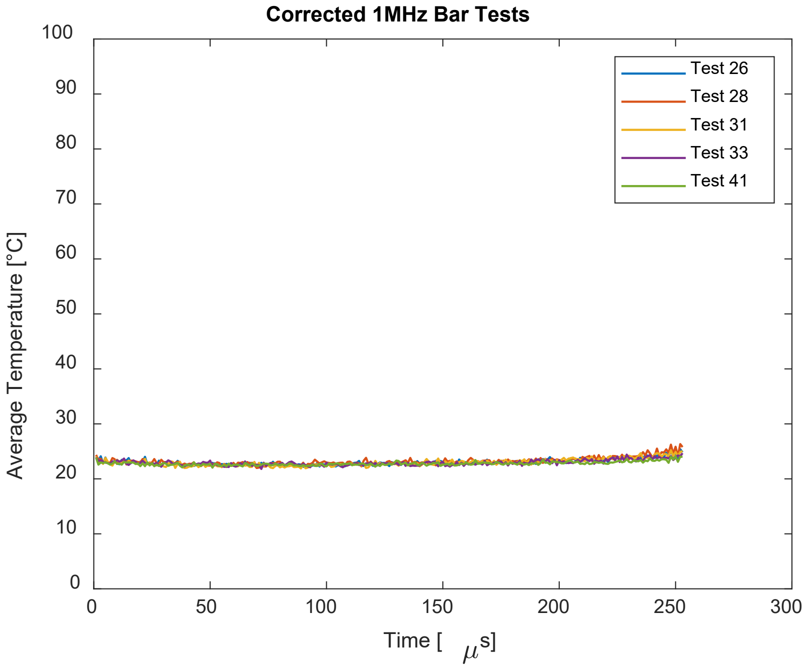


Figure 7: Temperature histories measured on the Sylgard samples have been incorrectly around room temperature, which is a problem identified for further examination.

Although the frame rate has exceeded the current state-of-the-art by an order of magnitude, the temperature measured was very low. Figure 8 shows the axial strain near the crack tip measured by DIC on the other side of the specimen. The strain field clearly shows highly concentrated regions that should, conceptually, lead to significant temperature rise.

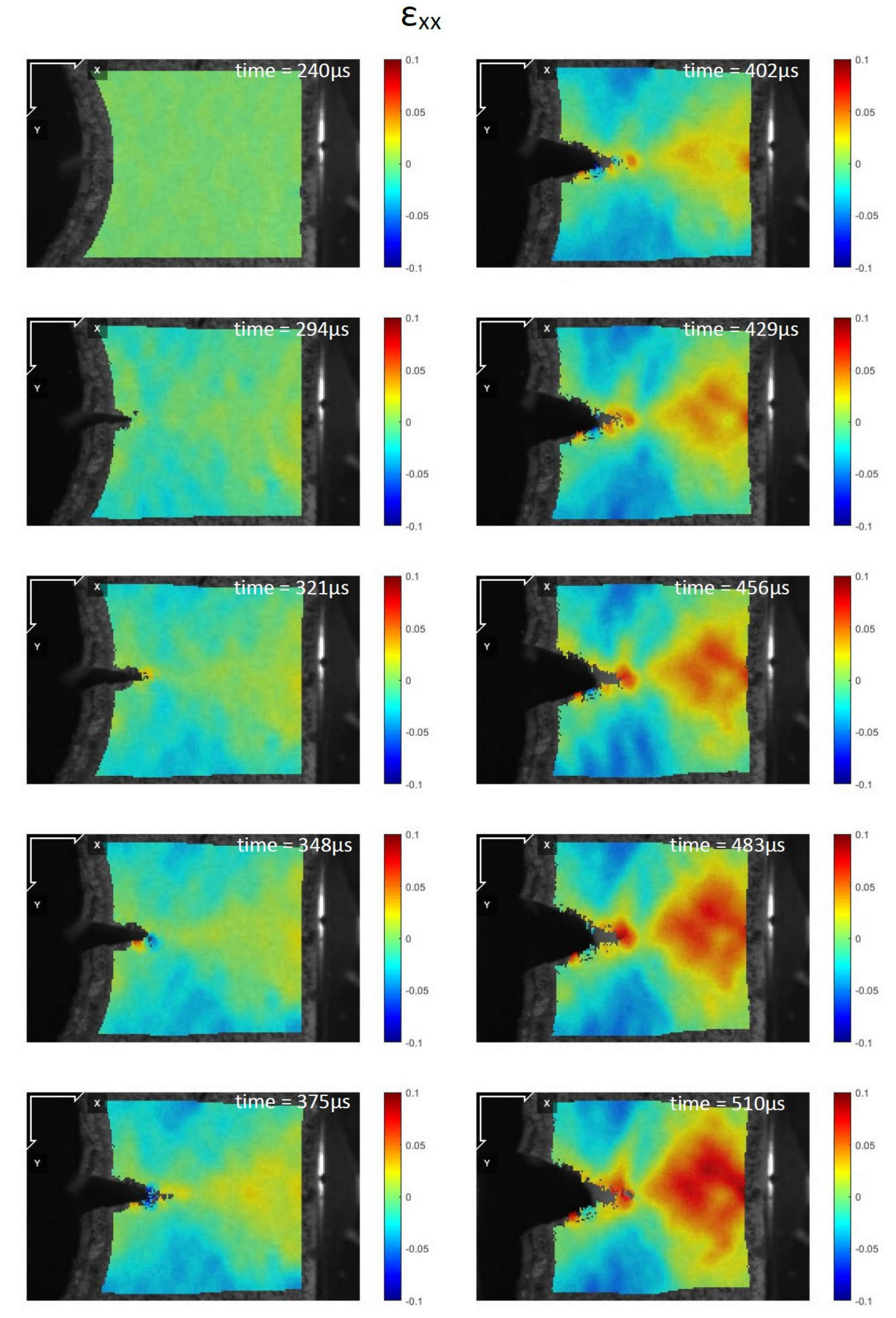


Figure 8: Axial strain field evolution during Kolsky bar test #39, which shows stress concentration near the opening crack tip in the Sylgard specimen.

To calibrate the temperature field, we used the same infrared high-speed camera for the work presented in Figure 3 to measure the dynamic temperature field on the Sylgard samples. The camera frame rate may not be high enough to capture the rise phase of the temperature on the sample. However, once the temperature is raised by stress-wave loading, the decay time through diffusion is much longer. The thermal camera will be able to capture the temperature field before it decays down. To increase the temperature in the sample, we used a gas-gun to impact the Sylgard samples at velocities an order of magnitude higher (~160 m/s). Figure 9 shows the temperature varying histories at two tracing points on the sample which was stricken at 169 m/s.

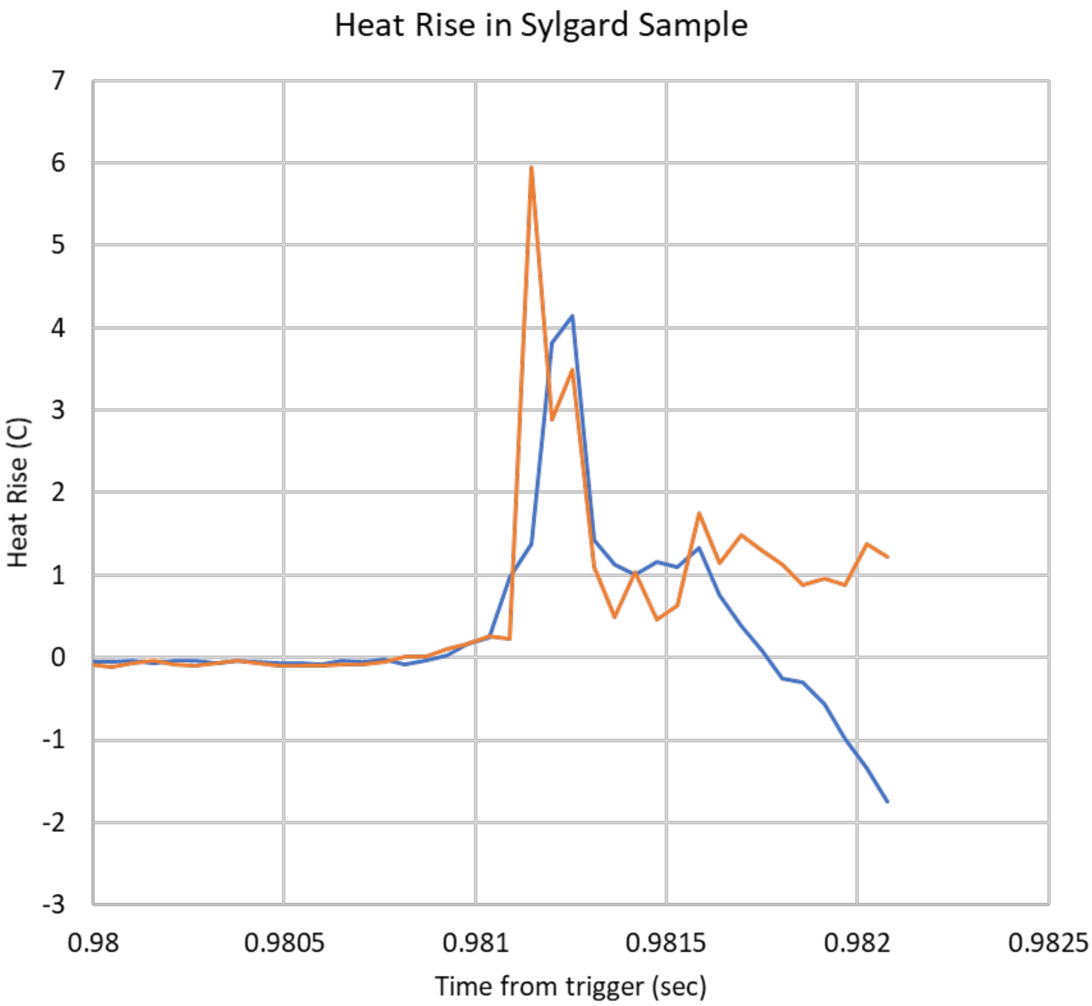


Figure 9: Temperature histories at two points in a Sylgard specimen during a gas gun impact at 169 m/s, which shows only a few degrees temperature rise even impact at much higher speed than in Kolsky bar. (Courtesy of Chase Wernex supported by ARL AAMP EM program)

The results in Fig. 9 show that, even impacted by a projectile at a striking velocity an order of magnitude higher than in Kolsky bar experiments, the temperature rise in the Sylgard specimen was only a few degrees above room temperature. This is in the same order of magnitude as the results shown in Fig. 7. We now have two different methods (thermal phosphors and infrared camera) that measured minimum temperature rise in Sylgard specimens under impact loading. Although this is unexpected, this may be the try behavior of Sylgard. We are now employing the second calibration method, but the time frame will be beyond this program.

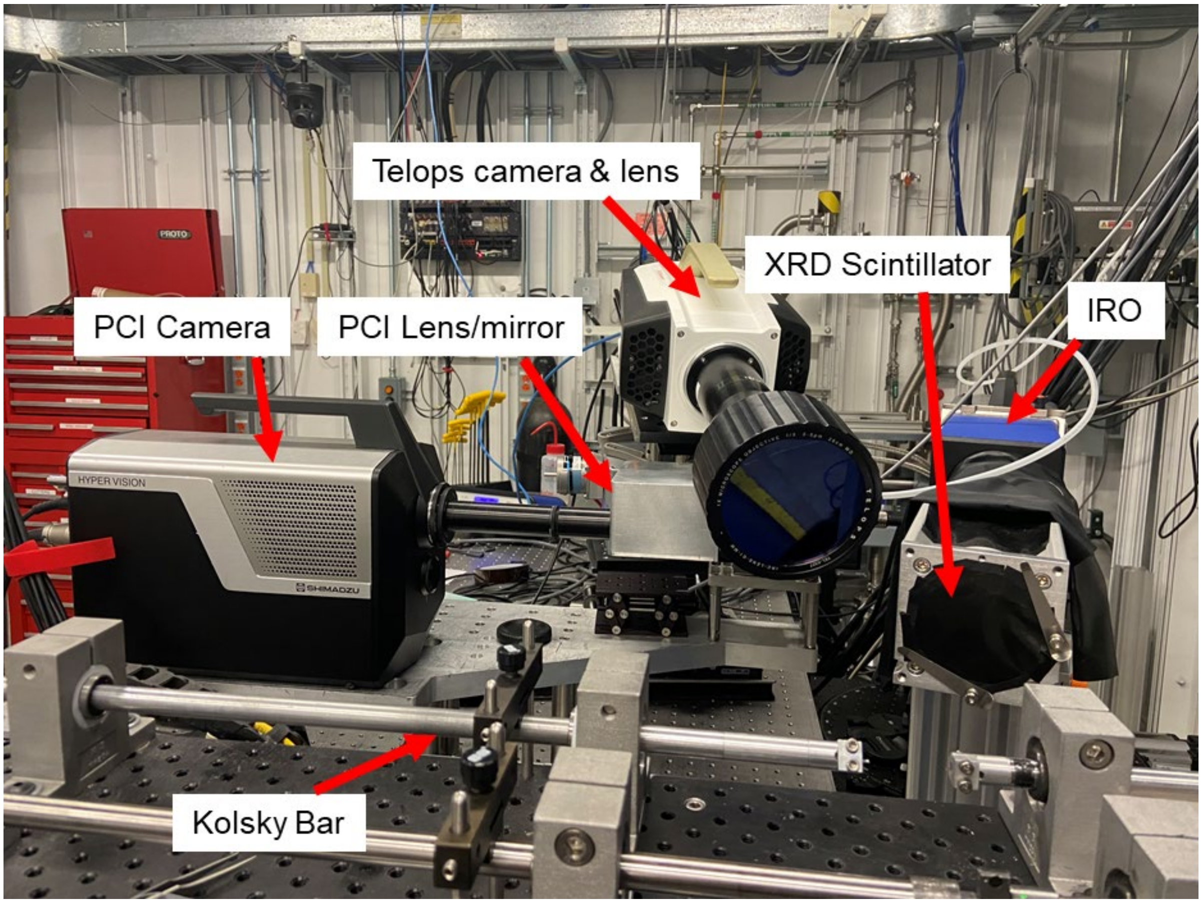


Figure 10: A Kolsky tension bar setup at 32 ID-B XSD, APS, Argonne National Lab with simultaneous high-speed X-ray PCI, XRD, and thermal imaging.

In the meanwhile, as shown in Figure 10, we have combined high-speed X-ray phase contract imaging (PCI), high-speed X-ray diffraction, and high-speed thermal imaging in one impact experiment to set the stage for future research aiming to reveal the inter connections among the material deformation, microstructure evolution, and temperature variation in the material under impact loading. We will be able to obtain the measurements in deformation, microstructure evolution, and temperature field evolution simultaneously, which is an unprecedented capability.

What opportunities for training and professional development did the project provide?

The program provided graduate students opportunities to learn and develop different experimental methods, as well as collaboration between two research groups (Chen group and Meyer group) at Purdue University, as well as with a group outside Purdue: Professor Amy Clarke's group at Colorado School of Mines.

How were the results disseminated to communities of interest?

3 Journal Articles (see at the end of the document for a list).

What do you plan to do during the next reporting period to accomplish the goals and objectives?

This program has ended. However, the research challenges continue. Based on the research supported by this program, we have developed more novel experimental methods that set the stage for further research. Proposals will be submitted to ARO.

Honors: What honors or awards were received under this project in this reporting period?

Nothing to report

Technology Transfer

Nothing to report

Participants

1. Type: Most senior project role
   Faculty
2. Prefix (optional)
3. First Name: Weinong
4. Last Name: Chen
5. Middle Name (optional): Wayne
6. Suffix

7. Nearest person month worked (a person month equals approximately 160 hours of effort, regardless of funding source): 1
8. National Academy Member? (Y/N)
9. Country if participant is a foreign collaborator: None.

Also, Terrence R. Meyer

Students

“Number of undergraduate and graduate STEM participants”: 2 (graduate students)

“Number of participants that received a STEM degree”: 0

Products

Journal Articles:

Nie, Y., Claus, B., Gao, J., Zhai, X., Kedir, N., Chu, J.-M., Sun, T., Fezzaa, K. and Chen, W.W., “In situ Observation of Adiabatic Shear Band Formation in Aluminum Alloys,” Experimental Mechanics, 60 (2020) 153–163. (Cover Article)

Zhai, X., Gao, J., Nie, Y., Guo, Z., Kedir, N., Claus, B., Sun, T., Fezzaa, K., Xiao, X. and Chen, W. W., “Real-time Visualization of Dynamic Fractures in Porcine Bones and the Loading-rate Effect on Their Fracture Toughness,” Journal of Mechanics and Physics of Solids, 131 (2019): 358–371.

Zhai, X., Nauman, E.A., Moryl, D., Lycke, R. and Chen, W.W., “Mechanical Anisotropy and Strain-rate Sensitivity of Human Front Skull Bone,” Journal of the Mechanical Behavior of Biomedical Materials, 103 (2020): 103597.