AFRL-AFOSR-VA-TR-2019-0021

Acquisition of State-of-the-Art 3D Dynamic Deformation Measurement System and Stereo-Microscope for Macro- to Micro-scale Studies with 200 Nano-second Temporal Resolution

Addis Kidane
University of South Carolina

01/18/2019
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTA1
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
12/29/2018	Final Report	09/30/2016-09/29/2018

4. TITLE AND SUBTITLE

DURIP: Acquisition of State-of-the-Art 3D Dynamic Deformation Measurement System and Stereo-Microscope for Macro to Micro-Scale Studies with 200 Nano-second Temporal Resolution

5a. CONTRACT NUMBER

FA9550-16-1-0623

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Addis Kidane and Michael A. Sutton

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

UNIVERSITY OF SOUTH CAROLINA
1400 WHEAT ST
COLUMBIA SC 29210-4112

8. PERFORMING ORGANIZATION REPORT NUMBER

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

USAF, AFRL DUNS 143574726
AF OFFICE OF SCIENTIFIC RESEARCH
875 NORTH RANDOLPH STREET, RM 3112
ARLINGTON VA 22203-1954

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution A: Approved for public release.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The support from AFOSR through a DURIP program is used to acquire ultra-high speed stereo vision-system incorporated with high magnification objectives and a high-speed infrared with high magnification GA1 lenseswas acquired by the support from AFOSR through a DURIP program. The ultra-high speed system was installed in October 2017 and has been used in two DoD-funded projects and other related projects. The high-speed infrared imaging was established in December 2018 and has been used to understand the hot spot formation in polymer bonded energetic materials, an area o

15. SUBJECT TERMS

Ultra-high speed, mesoscale, microstructure, Infrared, localization

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Addis Kidane
U	U	U	UU	7	**19b. TELEPHONE NUMBER** *(Include area code)* (803)-777-2502

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATE COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33315-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report. e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Final Report

Title: Acquisition of State-of-the-Art 3D Dynamic Deformation Measurement System and Stereo-Microscope for Macro to Micro-Scale Studies with 200 Nano-second Temporal Resolution

PI: Addis Kidane | Co-PI: Michael A. Sutton

University of South Carolina, Columbia

Abstract

The support from AFOSR through a DURIP program is used to acquire ultra-high speed stereo vision-system incorporated with high magnification objectives and a high-speed infrared with high magnification GA1 lenseswas acquired by the support from AFOSR through a DURIP program. The ultra-high speed system was installed in October 2017 and has been used in two DoD-funded projects and other related projects. The high-speed infrared imaging was established in December 2018 and has been used to understand the hot spot formation in polymer bonded energetic materials, an area of interest to the Department of Defense.

Objective

The acquisition of both state-of-the-art, ultra-high speed stereo-vision system (Ultra HS) and a unique stereo-microscope system that is integrated with the Ultra HS provides unprecedented ability to determine the three-dimensional surface deformations at up to 5,000,000 frames per second (40X higher than cameras with comparable resolution used with image correlation methods to quantify full-field strains) on specimens ranging from meters in diameter to a few millimeters in size. Together with existing dynamic testing facilities in our department (e.g., instrumented Charpy, split Hopkinson bar, torsional Hopkinson bar, tension Hopkinson bar, shock tube, drop-weight tower), acquisition of the proposed high speed imaging system will make our dynamic materials characterization facility well-equipped to tackle the main challenges in understanding the mechanics of heterogenous materials, at microstructure level, subjected to dynamic loading conditions.

The heart of our proposed Ultra HS for full-field three-dimensional dynamic deformation measurement system is a pair of synchronized Shimadzu HPV-X digital cameras. At the highest rates (5,000,000fps), the Ultra HS camera system utilizes stroboscopic illumination to obtain sufficient light and acquire high contrast images every 200 nanoseconds during the dynamic event; at frame rates below 500,000 fps, high-intensity diode lighting is adequate for illumination of the specimen. With the addition of the stereo-microscope system, it is important to note that both low and high magnification imaging is possible, providing the opportunity to study a range of structural and local dynamic events with unprecedented levels of measurement capability.

Status of Effort

As shown in Fig 1 and Fig 2. the support has acquired a state-of-the-art an ultra-high-speed stereo-vision system with a unique-high magnification objective and high-speed infrared camera with high magnification objectives from AFOR through a DURIP program. The ultra-high speed optical system comprises a pair of synchronized Shimadzu HPV-X digital cameras and infinity objective lenses. The high-speed infrared imaging comprises a high-speed infrared camera M3K and G1 high magnification lens.

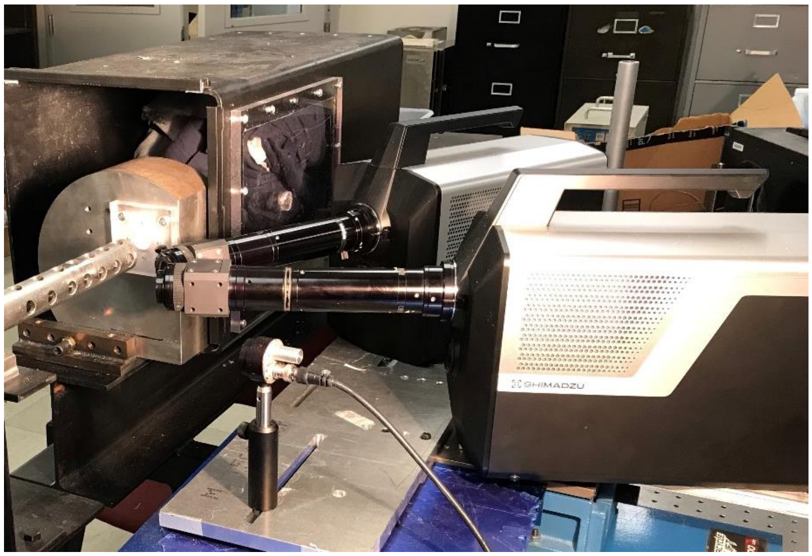

Fig.1 Ultra-high speed stereo imaging with high magnification objectives

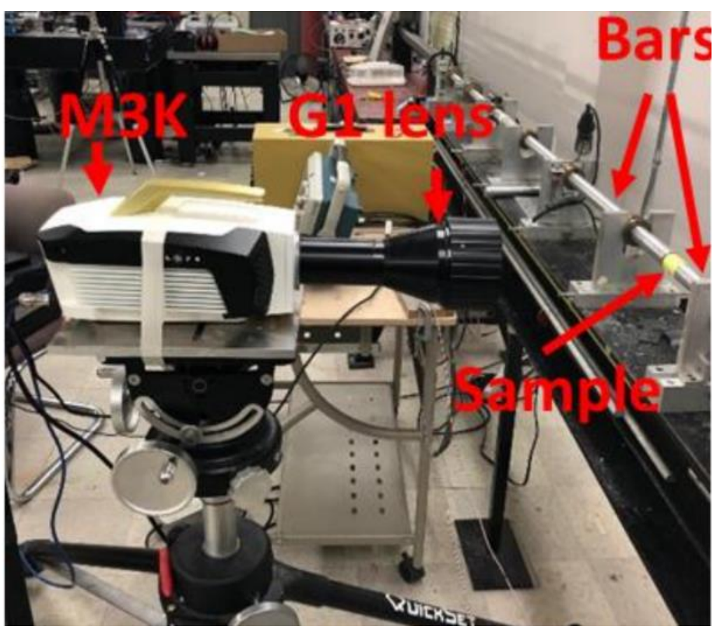

Fig.2. High-speed, high magnification infrared

Accomplishment /new findings

The primary objective of the project was to develop a high-speed imaging system that enables us to capture the local deformation mechanisms in materials subjected to high-speed loading at the microstructural level. Besides, the proposed imaging system will be instrumental in understanding the hot spot formation mechanism in energetic material under dynamic loading condition. As stated in the proposal, ultra-high stereo speed synchronized imaging PHV-X system with high magnification objectives, an Infinity K2 long-distance microscope, is acquired. The proposed method has been demonstrated by measuring the local deformation mechanisms of different materials such as polycrystalline magnesium, cellular material, polymer bonded energetic materials, and particulate nano-composites at a framing rate of 500 000 frames/sec and achieved a spatial resolution of 15.2 μm/pixel [1-9]. Further, the imaging system has been used to measure the local temperature rise in energetic materials to identify the hot spot formation mechanisms. Based on the measurement made through the developed method, it was identified that there are two primary mechanisms responsible for the formation of the shear band in polymer bonded energetic materials, the friction of crystals and plastic deformation of the binder. Depending on the loading rate and the mass fraction of the crystals, there will be a competition between the two mechanisms. To identify the predominant mechanism, one needs high-speed infrared imaging. The acquired high-speed infrared imaging is used to measure the local temperature field in polymer bonded explosives with main objective of determining the primary cause of hot spot formation. The research work conducted using the recently purchased systems is discussed below.

On the response of polymer bonded explosives subject to dynamic loading

AFOSR funded the project under grant number

The developed system is used to understand the failure mechanisms in polymer bonded explosives subjected to dynamic loading conditions. The effect of strain rate, compact pressure and mass fraction of the crystals on the local failure mechanism of energetic materials subjected to direct impact and shock loading is investigated. It was found that the mass fraction content has a significant influence on the response of the material and the mode of failure. It is observed that the dominant failure mechanism in higher solid loading samples under dynamic loading condition is crystal fracture. Whereas, in lower solid loading composition, a delamination dominated failure mechanism is observed.

The developed system is further used to investigate the compaction wave propagation in polymer bonded explosives. The compaction wavefront, compaction wave velocity and compaction wavefront thickness of PBS subjected to direct impact loading are measured experimentally. Meso-scale experiments under dynamic loading are also conducted to understand the local dissipation mechanism involved during the compaction front. Based on the full field data and non-parametric method, the spatial variation of the stress field in polymer bonded explosives is estimated for the first time. The damage evolution in PBX was quantified using volumetric strain and Poisson's ratio as an indication of damage incubation. The mesoscale study shows that the material softening due to damage evolution causes a wide shear banding in PBXs. Without the system developed through this grant, it would be impossible to get the information listed above.

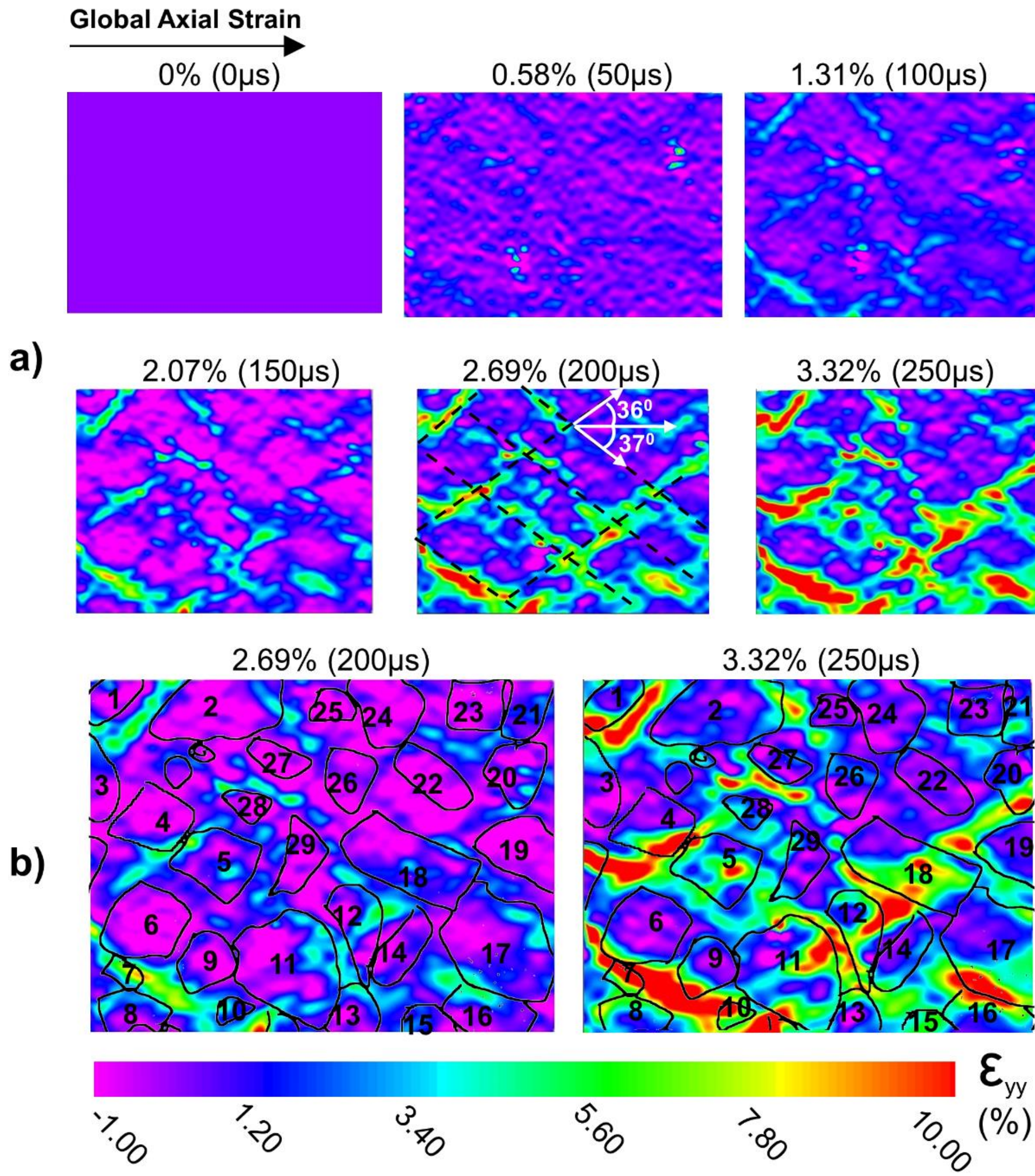

Fig. 3 Full filed local strain information obtained from the proposed systems a) Local transverse strain evolution as a function of loading time, b) a full filed image of a rain boundary overlaid on transverse strain field [3]

Mechanism of hot spot formation in polymer bonded explosives under dynamic loading

(An area interest to AFOSR)

Weak dynamic loading of polymer bonded explosives during transportation and handling may cause unintentional detonation which can be catastrophic and costly. These accidents are believed to be due to the formation of highly localized temperature regions called 'hot spots.' Due to a limitation in the experimental capability, experimental evidence of the hot spots and the understanding of the mechanisms of their formation are minimal. The systems acquired through this DURIP funding has been used to investigate the hot spot formation in polymer bonded explosives, using model composites under dynamic loading. The model composites used in this study are made of solid inclusions of graphite rods in the soft polymer, polydimethylsiloxane, binder. Using a high spatiotemporal resolution infrared camera and ultra-high speed visible light imaging based digital image correlation, the local temperature and deformation evolution are measured in-*situ* during dynamic loading of the sample. A significant heat generation and the high temperature was measured around the interface between the solid and the polymer binder as shown in Fig. 4. Interestingly, the deformation measurement indicates that the high-temperature generation could be associated with high relative movement between the solid inclusions and the binder.

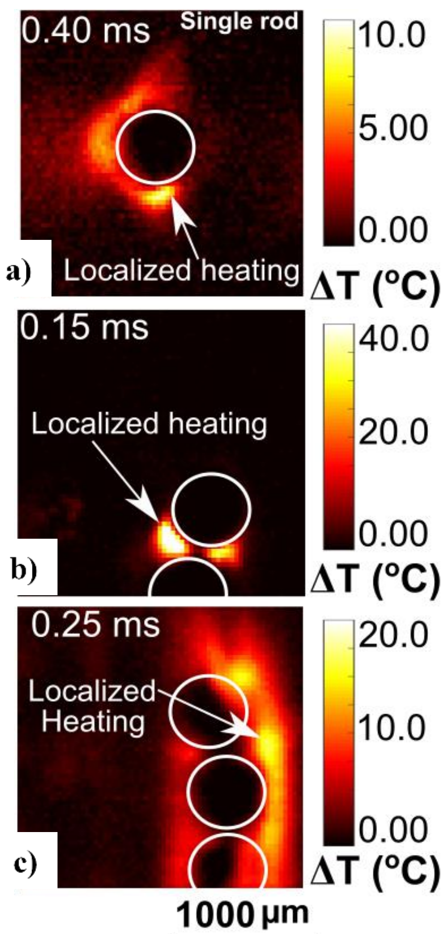

FIG. 4. Temperature evolution under dynamic loading measured by the acquired system. As shown in the figure the temperature is localized around the graphite rods a) single graphite rod, b) two graphite road surrounded by binder, c) three graphite rods. In all case the rods were aligned horizontally in the loading direction. The temperature is localized once the rods are rotated and reached in a vertical potion. Indicating temperature is generated by the student shear of polymer binder around the graphite rod

In-situ Quantification of Intra and Intergranular Deformation in Pure Magnesium Using Full-Field Measurements at Various Deformation Rates

Grain boundary cracking is almost an inevitable source of failure when a cast magnesium-based alloy is to be deformed at relatively low temperatures, due to the presence of weak grain boundaries as well as significantly coarse grains with minimal deformability. The acquired system is used to quantitatively investigate the contribution of inter- and intragranular deformation to the macroscale deformability and ductility of nominally pure as-cast magnesium subjected to quasi-static and dynamic loading. Mainly the system is used to investigate deformation and grain boundary cracking in cast magnesium subjected to quasi-static loading and for the analysis of mesoscale deformation and failure under dynamic loading conditions. A novel experimental setup consisting of a split Hopkinson pressure bar (SHPB) and a recently acquired ultra-high-speed imaging system is used for in-situ quantification of deformation at microstructural levels under high strain rate loading conditions. The results indicate that the contribution of grain boundary region deformation to the total strain applied on the Mg samples is significant and depends on the initial grain configuration. Also, strain rate sensitivity of the material was found to be controlled to a higher degree by the grain boundary region deformation [4].

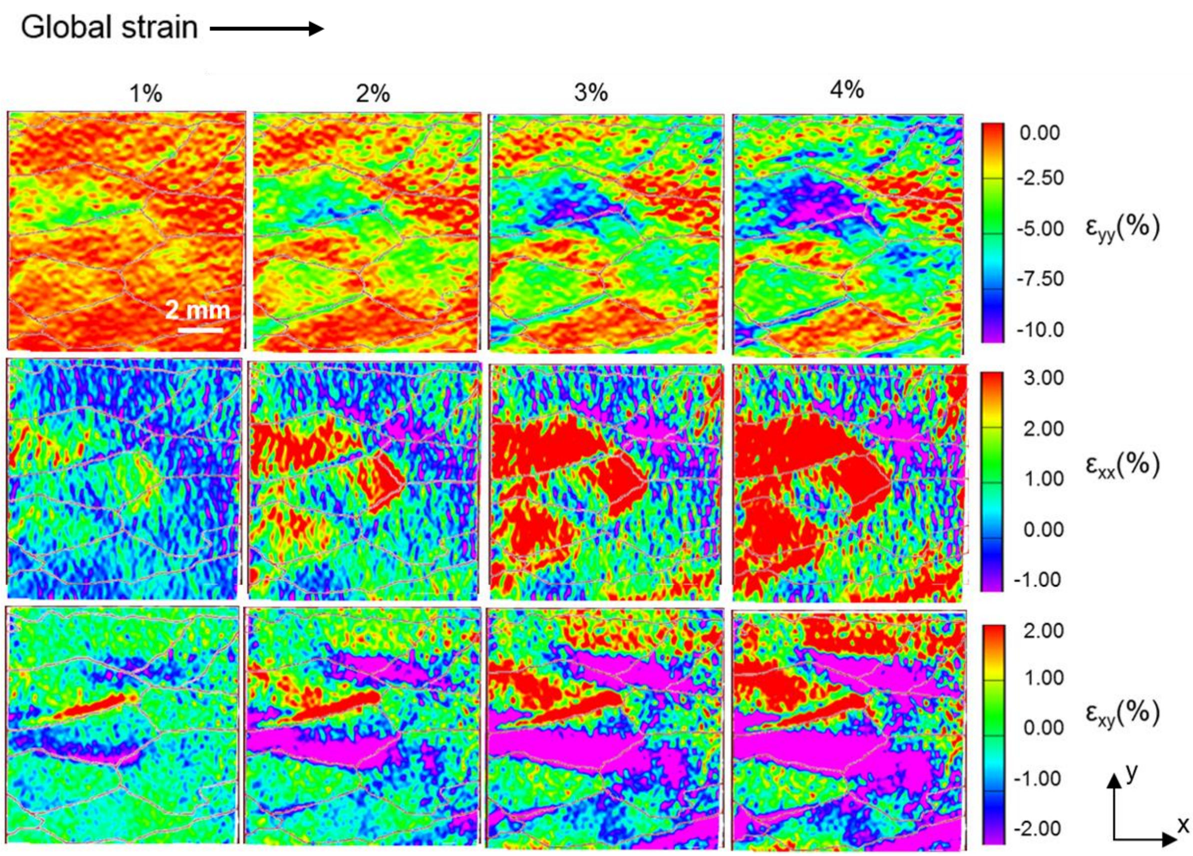

Fig. 5- Contour maps showing the evolution of in-plane strain components at different global strain magnitudes for a sample with grain orientation is perpendicular to the loading direction. Loading was applied in -*y*-direction. Grain boundary outline is overlaid on contour maps [4]

References

1. S. Ravindran* A. Tessema* and A. Kidane, Note: Dynamic mesoscale full-field surface deformation measurement of heterogeneous materials, Review of Scientific Instrumentation, 87 (3): 036108: 2016

2. S. Ravindran*, A. Tessema*, A. Kidane, Local deformation and failure mechanisms of polymer bonded energetic materials subjected to high strain rate loading" Journal Dynamic Behavior of Materials. (DOI: 10.1007/s40870-016-0051-9), 2016. (Selected for the best paper award)

3. S. Ravindran, A. Tessema, A. Kidane, Multiscale damage evolution mechanisms in polymer bonded sugars under dynamic loading, Mechanics of Materials, 114, 97-106, 2017

4. P. Malchow*, B. Koohbor*, S. Ravindran*, A. Kidane, In-situ Quantification of Intra and Intergranular Deformation in Pure Magnesium Using Full-Field Measurements at Low and High Strain Rates, Mechanics of Materials, 126, 36-46, 2018.

5. Malchow P., Ravindran S., Kidane A. (2019) Localized Microstructural Deformation Behavior of Dynamically Deformed Pure Magnesium. In: Kimberley J., Lamberson L., Mates S. (eds) Dynamic Behavior of Materials, Volume 1. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham

6. Ravindran S., Tessema A., Kidane A. (2019) On the Response of Polymer-Bonded Explosives at Different Impact Velocities. In: Kimberley J., Lamberson L., Mates S. (eds) Dynamic Behavior of Materials, Volume 1. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham

7. Suraj Ravindran, Peter Malchow, Addis Tessema, Addis Kidane, Compaction Wave Propagation Characteristics in Polymer Bonded Explosives at Macro-Meso Scale Dynamic Behavior of Materials, Volume 1,163-168, 2018 Springer, Cham

8. S Ravindran, P Malchow, A Tessema, A Kidane, Multiscale deformation behavior of polymer bonded explosives subjected to intermediate velocity impact, AIP Conference Proceedings 1979, 180008 (2018); DOI: 10.1063/1.5045041

9. S. Ravindran*, A. Tessema*, A. Kidane, Effect of solid loading on multiscale behavior of polymer bonded explosives under dynamic loading, Proceedings of the 2016 Annual Conference on Experimental and Applied Mechanics, Challenges in Mechanics of Time-Dependent Materials, Volume 2, ISBN: 978-3-319-41542-0, 2017