# Mesoscale *In-situ* Measurement of Deformation and Temperature of an Additively Manufactured Energetic Material Simulant under Dynamic Loading

A. Keyhani[1,2,a] and M. Zhou[2]

[1]Mechanical Engineering Practice, Exponent, Inc., 149 Commonwealth Drive, Menlo Park, CA 94025, USA,
[2]The George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405, USA

[a]akeyhani@exponent.com

**Abstract.** The mesoscale thermal and mechanical behavior of an additively manufactured energetic material (AMEM) simulant under dynamic loading is studied. The material is unidirectionally printed using direct ink writing (DIW) of a high solid-loaded photopolymer and cured under UV-light exposure. Experiments are performed to relate localized deformation, dissipation mechanisms, and temperature rises to the print structure. Simultaneous high-speed optical and infrared imaging is used to obtain deformation and temperature fields over the same area of samples with micrometer spatial and microsecond temporal resolutions. Loading along different directions relative to the print structure of the material is achieved using a split-Hopkinson pressure bar (SHPB) or Kolsky bar at the average strain rate of ~300 $s^{-1}$. Shear banding and shear failure are observed. The strain and temperature fields provide detailed first-time insight into the processes of fracture, friction, shear localization, and hotspot development in the microstructures.

## Introduction

The geometric flexibility provided by additive manufacturing (AM) or 3D-printing opens new avenues for functionally tailoring materials for specific applications. AM processes result in embedding inherent heterogeneities that can lead to poor mechanical properties and different mechanical behaviors in different directions and regions. Defects, microstructure heterogeneities, and anisotropy can significantly affect the behavior of additively manufactured energetic material (AMEMs) [1]. The focus here is the mesoscale thermo-mechanical responses under impact loading of a high solid-loaded photopolymer manufactured using the DIW process and cured with UV-light. The material mimics the attributes of some AMEMs. The experiments are performed in a SHPB or Kolsky bar apparatus at the average strain rate of ~300 $s^{-1}$, with the recently developed novel capability for simultaneous measurement of the temperature and deformation fields [2]. The technique involves the use of digital image correlation (DIC) for displacement and strain distribution quantification [3]. The deformation and temperature fields are coordinated to obtain understanding of the deformation, failure, and heating mechanisms in the material at the mesoscale.

## Technical Approach

The photopolymer composite used in the DIW AM and UV-light curing processes has a solid particulate volume fraction of 74%. The particulate population includes organic and inorganic materials. These printed blocks are approximately 37.8×54.5×13.3 mm in size (Fig. 1(a)). The samples are extracted from these blocks using a diamond saw. The samples are compressed without lateral confinement. Loading along 4 sample orientations relative to the AM print direction is considered. The 4 loading orientations are along the x direction, y (print or filament) direction, z (build) direction, and xy-diagonal direction. For this purpose, the samples are cut from the AM blocks accordingly at an overall size of 5×5×5 mm, as illustrated in Fig. 1(b). To capture the transient deformation and temperature fields over the same microstructure area of a sample with micrometer spatial and microsecond temporal resolutions, a high-speed visible light (VL) imaging camera and a high-speed infrared (IR) imaging camera are used. The two cameras capture the VL and IR parts of the emission spectrum from the sample, respectively. To separate these two parts, a dichroic beam splitter is used [2]. The VL and IR field of views (FOVs) are illustrated in Fig. 1(b).

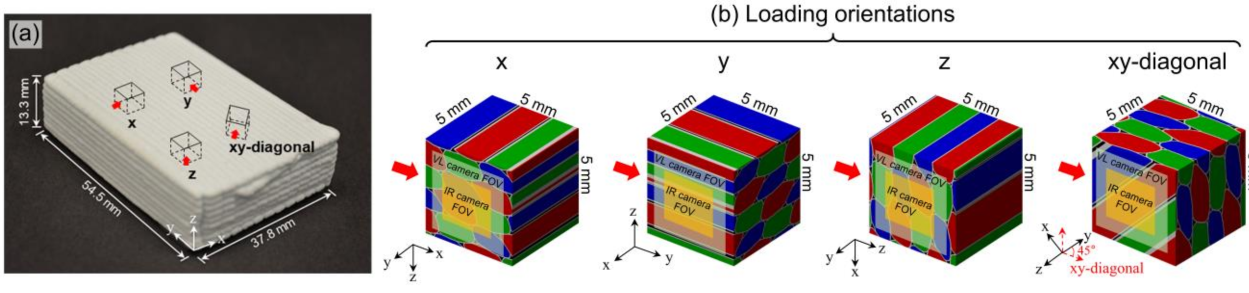


Fig. 1 Illustration of loading directions with respect to the print structure. The y and z directions are the print (filament) and build directions, respectively.

## Results

Under loading, the sample shows shear deformation and shear rupture. To quantify the deformation fields in the samples, DIC analyses are performed [3]. A total of 4 samples are studied at similar conditions. The DIC analyses concern the deformation fields up to the onset of shear rupture which occurs around $t$ =170-220 μs or overall strains of 3.4-5.9% for the sample set. Figure 2 shows the distributions of the maximum in-plane tensorial shear strain in the samples at the onset of rupture. The local maximum shear strain level at rupture is 4.8±0.8%. The shear band angle with respect to the loading direction is 33.6±5.3°.

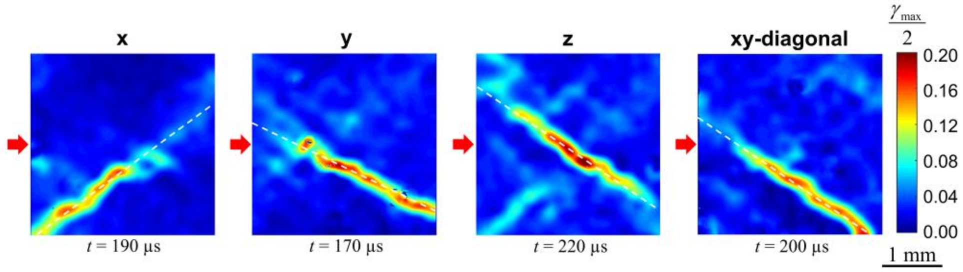


Fig. 2 Distributions of the maximum tensorial shear strain calculated at the rupture nucleation.

For loading in the x-direction, Fig. 3(a) shows the horizontal and vertical displacement fields and the corresponding temperature fields at $t$ = 300 μs and 600 μs. The displacement field on each side of the shear band is approximately uniform. There is no appreciable temperature increase away from the shear band. Figure 3(b) compares the profiles of the relative displacement and velocity across the shear bands (displacement and velocity jumps) with the temperature profiles at $t$ = 600 μs. The horizontal axis presents the distance along the bands. There is a correlation between the magnitudes of the relative displacement and velocity jump, their non-uniformity along the bands, and the temperature increases. The non-uniformity appears to be associated with the heterogeneous nucleation of cracks along the shear band paths.

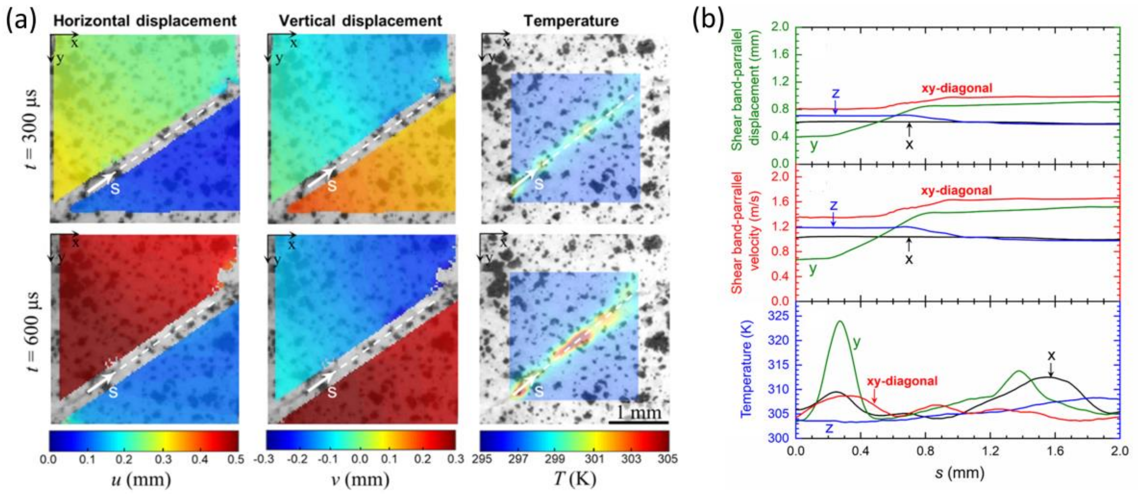


Fig. 3 (a) Displacement and temperature fields in the sample loaded in the x-direction at $t$ = 300 μs and 600 μs, and (b) profiles of relative displacement, velocity jump across shear bands, and temperature along the shear bands at and $t$ = 600 μs.

## Conclusion

Experiments are performed to analyze the dynamic thermo-mechanical behavior of an AMEM simulant whose base material consists of a photopolymer and solid particles. The mesoscale deformation, failure, and heating of the material under loading along four different directions with respect to the print structure are studied. Shear band development is the primary mechanism for deformation, heating, and ultimate failure. Post-rupture sliding along the shear bands is the primary heating mechanism and leads to significant temperature increases.

## Acknowledgement

This research is supported by the Defense Threat Reduction Agency (DTRA) through grant HDTRA1-18-1-0004 to Georgia Tech (Dr. Jeffery Davis).

## References

[1] A. Mueller, A. Schmalzer, P. Bowden, B. Tappan, A. White and R. Menikoff: Bulletin of the American Physical Society, Portland, Oregon (2019).
[2] A. Keyhani, R. Yang, and M. Zhou: Exp. Mech. Vol. 59 (2019), p. 775-790.
[3] J. Blaber, B. Adair, and A. Antoniou: Exp. Mech. Vol. 55 (2015), p. 1105-1122.