Mechanics of Energetic Materials: Development of High-Speed Visible and Infrared Diagnostics

Energetic materials, also known as reactive materials, are a class of materials in which dynamic loading (e.g. impact or shock loading) results in localized hot spots, i.e., regions of high temperature, due to a variety of mechanisms such as adiabatic shear bands, pore collapse under shock loading, friction, etc. Rapid chemical reactions are initiated at the hot spots, which may evolve into self-sustaining chemical reactions that could result in deflagration or detonation. Understanding the complete range of phenomena involved in the coupling between mechanical loading and reactivity of the material has been a long-standing challenge. Despite the progress that has been made, fundamental unanswered questions remain regarding the relative importance of the hot-spot formation mechanisms and the evolution of the collective response of populations of hot spots following dynamic loading. This is a growing area of activity in **Guduru**'s lab, with current focus on developing the much needed diagnostic techniques that can image and measure the dynamic deformation and temperature fields in energetic materials at extremely high spatial and temporal resolutions simultaneously. Such techniques are necessitated by the short time scales (sub-micro second) and length scales (~ microns) at which deformation localization leads to hot spots and nucleates chemical reactions. The subsections below describe the new diagnostic techniques and scientific instrumentation developed by **Guduru** towards imaging at high spatial and temporal resolutions simultaneously in the visible and infrared spectra. Beyond their applications in energetic materials, more broadly these techniques are valuable for understanding the dynamic deformation and failure mechanisms in heterogeneous materials at the meso-scale.

(i) Development of High-Speed Visible Microscopy: Although high-speed photography has been used in solid mechanics research for a long time, extending it to microscopic length scales has been a challenge due to a variety of technical challenges. **Guduru**'s lab has recently developed a technique that can achieve 250 ns time resolution and 0.6 micron spatial resolutions simultaneously. It employs a custom optics design, a fast high powered (400 W) pulsed laser source (pulse width as narrow as 5 ns) and a high-resolution rotating mirror type high-speed

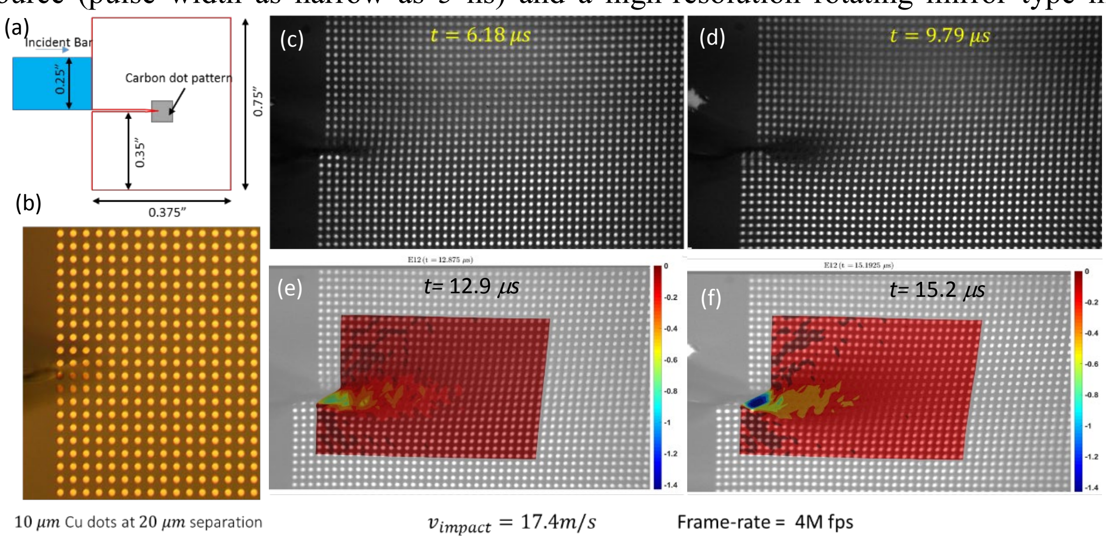

Figure 1. (a) Schematic impact configuration to induce an adiabatic shear band from a notch tip. (b) An image of the as prepared specimen showing a pattern of micro-dots around the notch tip, which is used to measure the strain field. (c)-(f) A sequence of high speed micrographs that capture the adiabatic shear band initiating from the notch tip. (e)-(f) show the extracted shear strain on top of the micrographs. The field of view in these images is 1.1 mm x 0.6 mm and the spatial resolution is ~ 1μm.

camera. The system was used to image an initiating and propagating adiabatic shear band and measure the associated transient strain field at an unprecedented spatial resolution. Figure 1 shows a representative sequence of high-speed images that captures an initiating adiabatic shear band. The micro-fabricated dots in the images are used to obtain the strain fields through a custom-developed particle tracking algorithm. Combined with the constitutive response of the material, this technique is ideally suited to understand dynamics of strain localization in a variety of materials, including molecular crystals (energetic materials) for which it will be employed next.

(ii) Development of High-Speed Infrared (IR) Microscopy: Although the importance of hot spots in energetic materials has been well recognized and substantial progress has been made in computational modeling of the possible mechanisms, there have been practically no accurate measurements of the actual temperature fields. As a result, it has not been possible to verify or validate the computational models, and thus their predictive ability of the actual phenomena remains an open question. The reason for the lack of experimental measurements of the temperature fields has been the lack of an experimental tool to image and measure the temperature fields at the required time and spatial resolutions. For instance, the fastest commercially available infrared thermal imaging system captures images at a rate of a few kHz. However, the relevant localization events in dynamically deforming solids occur over time scales of the order of micro-seconds, which is orders of magnitude faster than what the existing systems are capable of handling.

In order to address this critical gap in diagnostics for energetic materials, as part of an AFOSR funded program, **Guduru** has developed a high speed infrared imaging system capable of 1 - 10 million frames per second. Its spatial resolution can be adjusted to be between 10 μm and 30 μm for small temperatures increases above the room temperature. The spatial resolution can be reduced further for higher temperature increases at which the peak wavelength of the IR radiation shifts to lower values. The system is designed, developed and integrated at Brown, except for a few components that have been outsourced to companies with specialized technologies. Full details of the system are not provided here since the intellectual property disclosures on the system invention are currently being pursued. A preliminary description of the system and its capabilities are summarized in Figure 2.

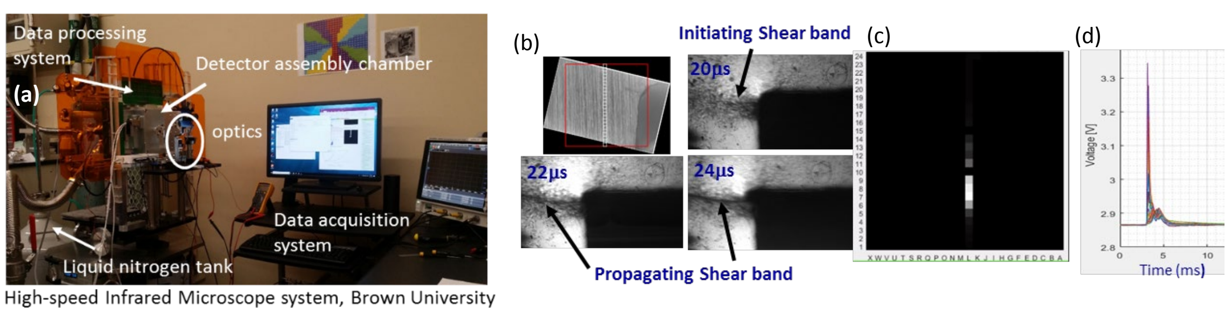

Figure 2. (a) A photograph of the high speed infrared microscopy system, capable of imaging at up to 10 million frames per second. In a preliminary demonstration, the system is employed to image the temperature field corresponding an propagating adiabatic shear band in a structural alloy. Both high speed visible microscope and the high speed IR microscope are employed on either side of the sample simultaneously. (b) A sequence of high speed visible microscopy images of an adiabatic shear band emerging from a notch tip (FOV:1.1mm x 0.6mm). (c) The corresponding thermal field at one instant as measured by a column of pixels as the shear band passes across it (FOV: 0.7mm x 0.7mm). (d) Time history of the thermal field measured by the individual pixels.