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Real-Time Full-field Deformation Analysis on the Ballistic Impact of Polymeric Materials Using High-speed Photogrammetry

by Jian H. Yu, Alex J. Hsieh, Peter G. Dehmer, and James M. Sands

ARL-RP-0290 **April 2010**

A reprint from the *American Society for Composites 2009 – 24th Technical Conference*,
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ABSTRACT

The dynamic deformation of transparent polymeric materials during the ballistic impact is investigated using a unique high-speed imaging technique. This technique involves the use of two high-speed cameras to record stereo images of a speckle patterned impact area and subsequent photogrammetric analysis. Photogrammetry is an image correlation technique that determines geometric properties, such as the displacement and strain history of a deformation event, by tracking the minute changes in the speckle pattern on the area of interest. These minute changes are then translated into three-dimensional displacement vectors as a function of time. Important mechanical behavior, such as strain or shear angle, can be calculated from the displacement vectors. By combining high-speed photography with photogrammetry, a full-field view on the strain as a function of time is made possible, and the strain can be resolved into components, such as the principle strain and shear strain.

To demonstrate the capability of the high-speed photogrammetric technique, impact measurements on two different polymers were performed. A steel spherical projectile with a diameter of 5.54 mm and a weight of 0.692 g was used to impact a rigid polycarbonate (PC) and a flexible poly(urethane urea) (PUU) elastomer. The measurements were carried out at striking velocities between 100 m/s and 200 m/s, below the ballistic limits of both materials. At low impact speeds, the strain histories revealed that PC had a smaller deformation zone than PUU. At high impact speeds, it was observed that PC suffered a permanent strain deformation, whereas the strain in PUU relaxed over time. From these impact experiments, it is demonstrated that high-speed photogrammetry is able to capture the different strain behavior of these two polymers. These real-time strain histories cannot be easily observed quantitatively by other methods.

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1. Introduction

The real-time image analysis of a dynamic deformation is essential for the study of crack propagation and ballistic impact of polymeric materials. Photogrammetric analysis is a valuable tool for performing optical measurement of mechanical motion. With the advent of digital imaging, photogrammetry becomes a versatile optical technique for the measurements of full-field displacement and strain. It not only can measure in 2D and 3D spaces, but also can perform measurements in both fluid and solid materials.

Photogrammetry is an image correlation technique that determines geometric properties, such as the displacement and strain history of a deformation event, by tracking the minute changes on the area of interest. Chu and co-workers have pioneered the early works in developing the digital photogrammetric technique for experimental stress analysis [1,2,3]. Photogrammetry has been applied in many fields of study such as biomechanics [4,5], structural engineering [6,7], and ballistics [8,9]. There has been a strong effort to develop a robust photogrammetric technique for mechanical deformation analysis. [10,11,12].

Here, a report on the development of a high-speed photogrammetric system for the study of ballistic impact is presented. This technique involves the use of two high-speed cameras to record stereo images of a speckle pattern on the impact area and the subsequent photogrammetric analysis. Real-time full-field displacement and strain measurements were obtained on two different polymers, polycarbonate (PC) and poly(urethane urea) (PUU), during high-speed impact experiments. Comparisons of the molecular influence between PC and PUU on the high strain-rate mechanical behaviors, which include both strain and shear deformations, are included.

2. Experimental Methods

Ballistic impacts were carried out with a 0.22 CAL gas gun. The projectile used was a 5.56 mm diameter stainless steel ball bearing (Type 302) that weighs 0.69 g. The gas gun was pressurized at different pressures with helium gas to propel the projectile at selected impact speeds. The speed of the projectile was tracked with a Doppler radar (BR-3502, Infinition Inc.). The polymer target (20 cm x 15 cm x 0.3 cm) was sandwiched in a target frame with a circular opening of 7.62 cm in diameter. The PC target was prepared from general purpose grade Makrolon® (Bayer, USA). The PUU target was provided by Triton Systems Inc (Chelmsford, MA). The cast PUU sheet was synthesized from 4,4′-dicyclohexylmethane diisocyanate and poly(tetramethylene oxide) with diethyltoulenediamine as the chain extender [13]. The targets were painted with a random pattern of white and black dots (Figure 1). The dot size that appeared on the digital image was about 8 pixels in diameter.

Two high-speed cameras (Photron SA1, Photron USA, Inc.) were used to generate stereo image pairs of the impact area (Figure 2). The two cameras were placed behind the target fixture. The angle between of the cameras was set to 20^{o}. The images were recorded at 256 x 256 pixels resolution. The frame rate was set at

67500 frames-per-second. The exposure on each frame was 1/67500 s. Each camera was attached with a macro-lens (Nikon AF-Nikkor). The focal length and the f-stop were set at 35mm and f/8, respectively. The field of view was about 5 cm x 5 cm and it was centered on the location of the impact point. The images were saved as 8-bit TIFF files.

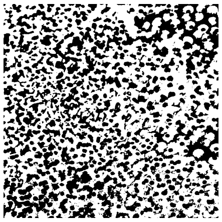

Figure1. Painted pattern on the back surface of the target (5 cm x 5 cm field-of-view)

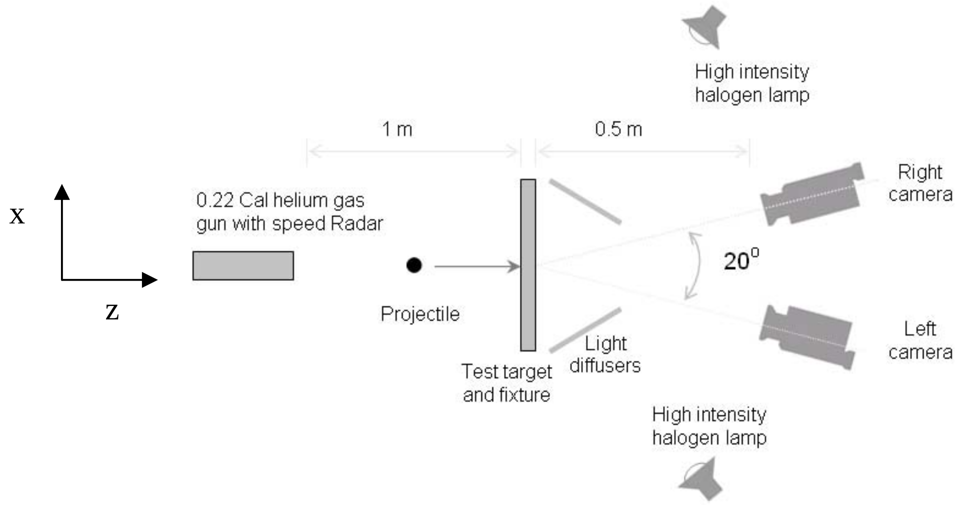

Figure 2. Impact experiment setup and cameras placement

The stereo images were analyzed using a commercially available photogrammetric software program called *Aramis* (GOM GmbH, Germany, distributed by Trilion Quality Systems in the USA). The cameras were calibrated with a series of standard dot images [11]. *Aramis* has a built-in algorithm for calculating the displacement. It divides the picture's pixels into groups called facets and then tracks their movement. The center pixel on the facet represents the displacement point. For 256 x256 pixels images that have painted dot sizes of 8 x 8 pixels, the optimal facet grouping density is 15 x 15 pixels per facet. The number of displacement points available for calculation can change by altering the facet overlapping distance. For example, if the overlapping distance changes from 13 pixels (i.e. the initial distance between the center pixels) to 8 pixels, the number of displacement points available for calculation would increase by twofold. Figure 3 shows two 15 x 15 facets on top of the painted target with an 8 pixels overlapping distance. Each pixel represents 0.229 mm by 0.229 mm.

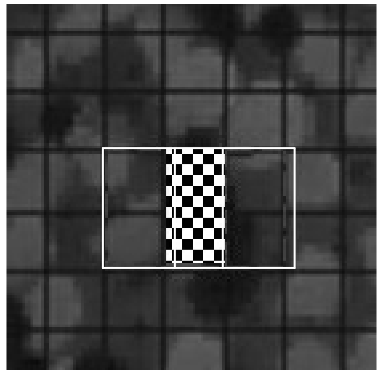

Figure 3. Two 15 x15 square facets overlapping each other; the checkerboard area indicating the overlapping pixels

3. Results and Discussion

3.1 Displacement measurement sensitivity test

To assess the accuracy on the measured displacement, 50 pairs of images were taken on the target area at rest over a period of 50 milliseconds. Figure 4 shows the displacements at the center of the field of view (0, 0, 0) during the period. The out-of-plane (z-direction) measurements fluctuate between 0.025 mm and -0.025 mm, whereas the in-plane measurements (the x- and y- directions) have small fluctuation between 0.005 mm and -0.005 mm. The intrinsic *Aramis* measurement sensitivity is about 0.0033 mm, according to the manufacturer [ref 11]. The fluctuations on the measured displacements are mostly due to ambient vibrations. The out-of-plane measurements have a strong dependency on the distance between camera lens and the image plane, whereas the in-plane measurements do not [2,9]. Thus, the fluctuation in the z-direction is amplified.

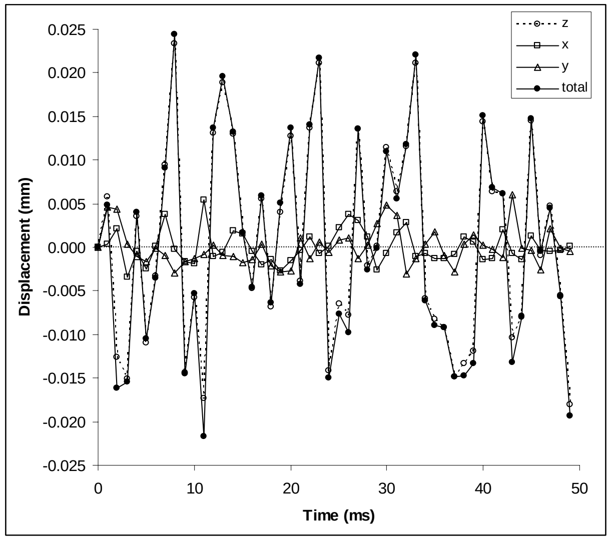

Figure 4. Fluctuations on the measured x-, y-, z- and total displacements

3.2 Strain calculation sensitivity test

Aramis has a built-in linear strain algorithm to calculate the surface strain base on the measured displacement points. A few researchers have used *Aramis* to calculate the strain in their experiments [14,15]. They reported less than 1 % error in the strain calculation. However, the linear strain calculation ignores the curvature between the displacement points. It works well in 2D tensile strain calculation where there is no curvature in the z-direction. In 3D deformation experiments, the strain calculation is sensitive to the number of overlapping pixels between facets (i.e. the number of pixels between facets centers).

To determine the strain calculation sensitivity, the Largrangian strains at each displacement point were calculated for various pixel overlaps for a PC target that was impacted by a steel ball at 108 m/s. The strain in the x-direction, ε_{xx}, was calculated at the time when it reached its maximum value. The material strain line was calculated along the x-axis (Figure 5). The Largrangian strain is defined as:

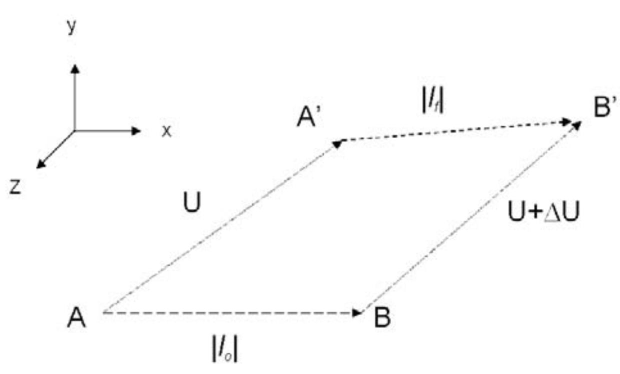

Figure 5. Line AB that parallels to the x-axis with length, l_o, is subjected to a uniform strain field, where U is the displacement vector and A'B' is length after the deformation.

$$\varepsilon_{xx} = \sqrt{1 + 2\frac{\partial U_x}{\partial x} + (\frac{\partial U_x}{\partial x})^2 + (\frac{\partial U_y}{\partial x})^2 + (\frac{\partial U_z}{\partial x})^2} - 1 = \frac{|l_f| - |l_o|}{|l_o|} \quad (1)$$

The length of Line AB is the un-deformed distance (number of pixels overlapped) between the facet centers. Figure 6 shows the strain calculations from each pixel overlapping density. At low strains, below 8 %, the calculated strain values do not vary more than 0.25% between each set of data. Whereas at high strains, the calculated strains at the impact point vary from 12.4% to 15.0 %. As the pixel overlapping density increases, the calculated strain value increases as well. Due to the shortening of the distance between the facet centers, the local curvature is taken into account during the calculation. However, as the overlapping density increases beyond 10 pixels, the background noise begins to disguise the local curvature and the calculated result is no longer valid.

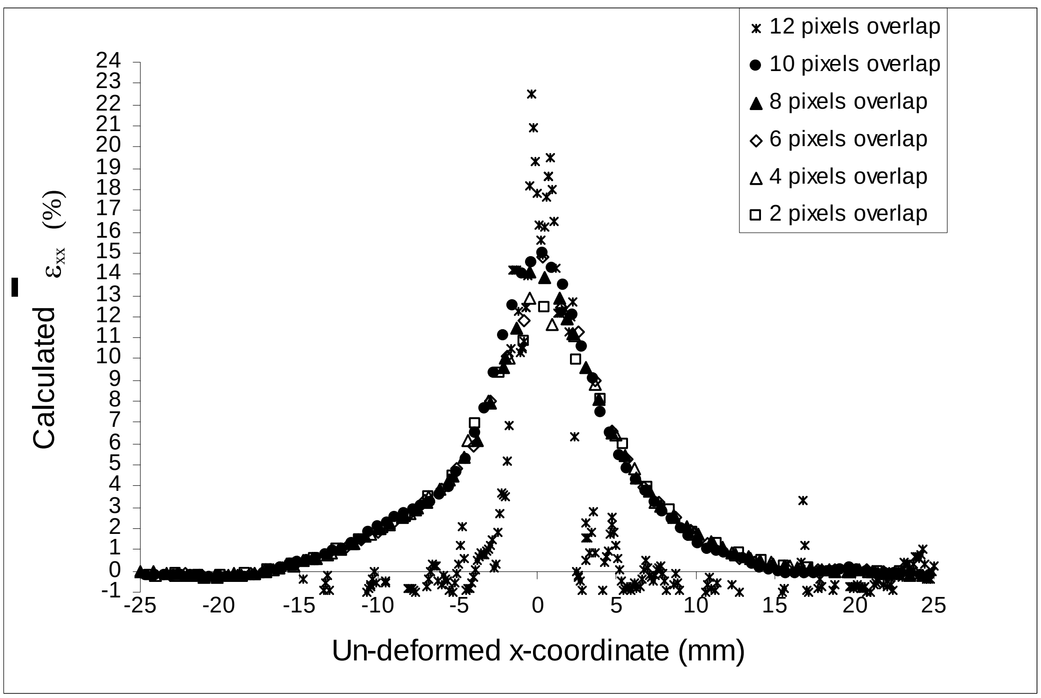

Figure 6. Calculated strains for different pixel overlap densities; impact center at the origin (0,0,0)

3.3 Full-field deformation measurements

Full-field displacement and strain measurements on PC and PUU during high-speed impact were performed using an 8 pixels overlap. PC is a rigid thermoplastic, whereas PUU is a microphase-separated elastomer and has a soft-segment glass transition temperature well below the ambient temperature [13]. Figure 7 shows a sequence of full-field displacement images at an impact speed of 108 m/s. At low impact speeds, PC has a smaller deformation cone than PUU. From the full-field displacement profiles, it was observed that the impact energy was dissipated by the global bending deformation from these two polymers. Both PC and PUU were not permanently deformed at low impact speeds. At high impact speeds near the ballistic limit of the two polymers, the localized deformations became dominant. It was observed that PC suffered a permanent strain deformation, whereas the strain in PUU could relax away over time. Figure 8 displays the evolving shear strain as a function of time. The shear bending zones are localized at the impact area. The deformation on the PC was beyond the limit of elastic deformation. A permanent indentation on the PC target was observed. The PC target would eventually fail by plugging. The glass transition temperature of PUU, however, is below room temperature; it remains in a rubbery state. The molecular makeup of the PUU allows it to recover from the deformed shape. In contrast to PC, the failure mechanism leading to the penetration of the PUU target was a rubbery failure.

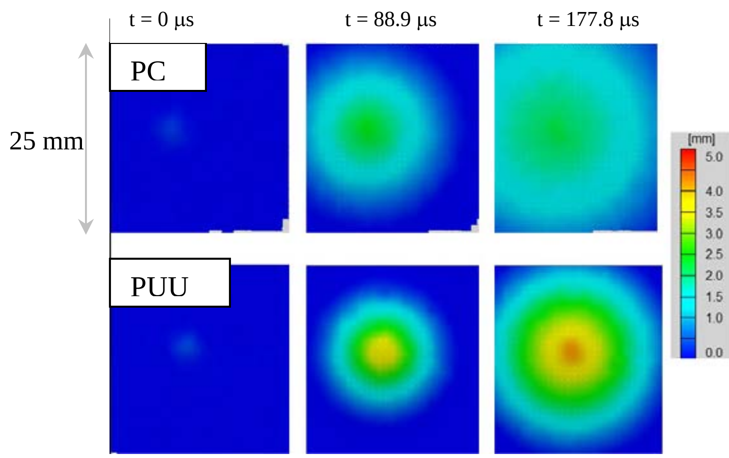

Figure 7. z-direction displacement profiles after impact at speed of 108 m/s

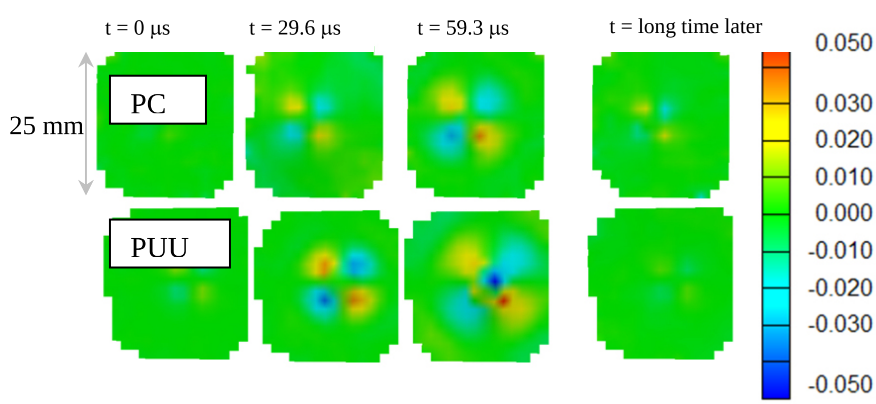

Figure 8. Shear strain profiles after impact at 188 m/s

4. Conclusions

High-speed photogrammetry has been developed to record the deformations of two different polymers, a rigid PC and an elastomeric PUU, during ballistic impacts. The measurement sensitivity has been validated. The displacement accuracy is within $\pm$ 25 microns. Most of the error in 3D measurement is due to background vibration in the z-direction. For 2D measurement, the accuracy is within $\pm$ 5 microns. The pixels overlapping density strongly influences the strain calculation. A high overlapping density is needed where there is a local curvature. Experimental results clearly indicate that high-speed photogrammetry is capable of revealing and differentiating the strain histories between these two materials, which cannot be easily observed quantitatively by other methods.

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