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Dynamic Fracture Process during Three-Point-Bending Impact on Polymethyl-Methacrylate Beams

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Abstract- Dynamic fracture process in polymethyl-methacrylate (PMMA) beamshave been investigated during the three-point-bending impact tests at different imapct velocites, conducted in a drop-weight impact tower instrument. The impact-induced crack initiation and propagation have been recorded with a high-speed camera, to determine the instantaneous fracture length and crack velocity during impact process. The beam deformation and displacement fields were extracted and analyzed by using the digital image correlation (DIC) thechnique during the impact. The impact loading history has been recorded with a load cell attached to the dropping weight. Thewhole experimental studyis a suitable technique to determine the influence of the impact velocites (impact energy) on the dynamic fracture initation and propagation at different crack speeds.

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Dynamic Fracture Process during Three-Point-Bending Impact on Polymethyl-Methacrylate Beams

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Abstract- Dynamic fracture process in polymethyl-methacrylate (PMMA) beamshave been investigated during the three-point-bending impact tests at different imapct velocites, conducted in a drop-weight impact tower instrument. The impact-induced crack initiation and propagation have been recorded with a high-speed camera, to determine the instantaneous fracture length and crack velocity during impact process. The beam deformation and displacement fields were extracted and analyzed by using the digital image correlation (DIC) thechnique during the impact. The impact loading history has been recorded with a load cell attached to the dropping weight. Thewhole experimental studyis a suitable technique to determine the influence of the impact velocites (impact energy) on the dynamic fracture initation and propagation at different crack speeds.

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I. Introduction

Dynamic fracture in structural materials is a significant issue because it concerns the failure of structural materials in their dynamic service. Impact is one of the most common dynamic loading forms but complicated since the material properties and failure behaviors are complex in dynamic situation. The dynamic fracture problems have been studied experimentally [1–3] and numerically [4,5]. Joudon[1]studied the dynamic stress intensity factor by using a strain gauge method associated with high speed cinematography on a three-point-bending test with specimens made of M21 epoxy resins. Cramer[2]conducted dynamic fracture experiments using boron-doped silicon single crystals followed by cleavage fracture with the propagation of a faceted crack front with amorphous materials. Owen[3]studied the critical dynamic stress over a range of loading rates of 2024-T3 aluminum sheets ranging in thickness from 1.63-2.54 mm.The dynamic fracture process in three-point-bending beams made with isotropic polymer [4] and orthotropic composite materials [5] have been numerically simulated with peridynamics.

Fracture in PMMA have also been studied. Takahashi [6]investigated multiple dynamic fracture parameters such as the dynamic stress intensity at thecrack tip as well as crack velocity and acceleration. They analyzed the initiation and propagation behavior of the crack of thin PMMA sheet under tensile load. Lataillade [7]studied the mechanical behavior of PMMA under various loading rates as well as the properties of the polymer at high rates of strain. Their research identified the relationship between Young's modulus, yield stress and fracture toughness of PMMA and tensile loading rates. On the other hand, Loya [8]performed quasi-static three-point bending test on PMMA beams and recorded the crack-front propagation process throughout the specimen thickness. The crack-lengthand the average steady crack propagation were extractedand studied. In a more recent study, Huang[9] adopted a different technique, dynamic semicircular bend testing, and performed fracture testing on PMMA specimen with split Hopkinson pressure bar. Their study determined the fracture velocity under different loading rates as well as surface fracture toughness and its relationship with fracture energy.

However, the impact-induced dynamic fracture process in PMMA with precise record of crack propagation and speed has rarely been studied before, especially the fracture caused by impact with different velocities. In the former studies, therecording time step period is relatively long. For example, only the average crack velocity for the whole fracture can be obtained. To better understand more detail dynamic fracture process, including the beam deformation and crack propagation, the more precise experimental investigation in more precise time steps is essential.

In this paper,the impact-induced dynamic fracture process in PMMA beams has been investigated. The experiment was conduceted with a drop-weight tower instruments. During the impact test, the impact loading history has been recorded by a load cell attached to the bottom of the dropping weiht. The impact process was recorded the with a high-speed camera at the time resolution of about 15 microseconds. The impact-induced crack initiation and propagation have been extracted fromthe images recorded with the high-speed camera, to determine the instantaneous fracture length and crack velocity during

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impact process. The beam deformation and displacement fields were calculated and extracted by using thethe digital image correlation (DIC) thechnique. The fracture in beams subjected to different impact velocities have been compared and analyzed.

II. Experimental

a) Experiments setup

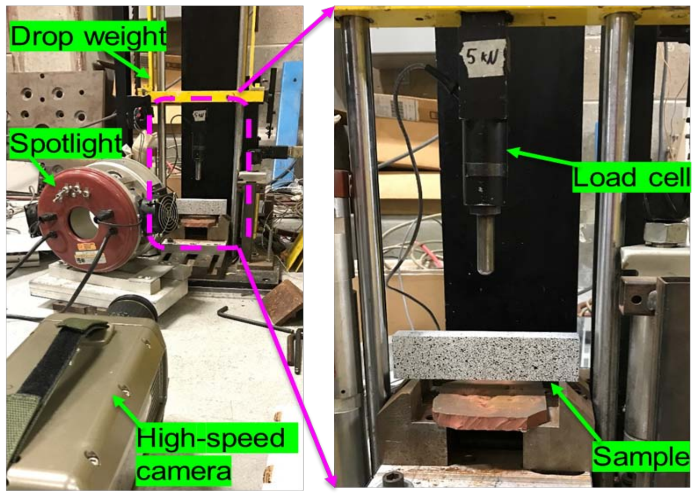

Figure 1: Drop weight impact experimental setup

The experiment was conducted by performing a three-point-bending impact test on a single-edge-notched PMMA specimen by using a drop-weight impact tower as shown in Fig. 1.The dropping weight was located above the PMMA sample and set free to drop onto the sample surface. Three impact velocities (1, 2, and 3 m/s) were achieved by dropping the weight from three different heights. To monitor the force applied during the experiment, a load cell was attached to the bottom of the dropping weight, which is used to record the loading signals during the impact process. The signals from the load cell then can be amplified by an amplifier, then displayed and recorded with an electronic oscilloscope provided by National Instruments. A high-speed camera was placed perpendicular to the vertical surface of the specimen to record the video of the impact process, which can be used to extract the crack propagation details and the corresponding displacement fields at different time steps.

The sample beam is made with PMMA (purchased from McMaster-Carr) with the length of140*mm*, thewidth of38*mm*, and height of 25.4*mm*. A notch of 16*mm* was initially made in the center of the bottom edge of the plate as shown in Fig. 2.

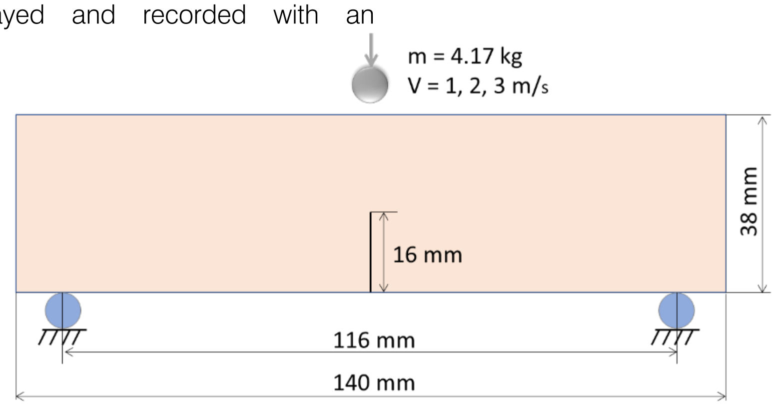

Figure 2: Impact experimental setup of PMMA beam

b) Displacement field extraction with digital image correlation (DIC) method

The DIC method is an optical method of experimental mechanics that can be used to measure and calculate the displacement, deformation, and strain field of the objective samples during mechanical testing[10–12].White background painting with evenly located black speckles painting was sprayed on the surface of the samples for the DIC testing. The size of the black painting speckles and the appropriate

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distances between each speckle can be determined by the suggestions in[13].A fully prepared specimen surface was shown in Fig. 3.The camera was set to focus on the crack propagation region on the specimen. The resolution of the camera was 256 x 256 pixels, which correlated to the square area at the center of the specimen.A sequence of images were extracted from the video with time incremental of 5 milliseconds. The images were then inputted into software GOM correlate for displacement field and crack propagation analysis.

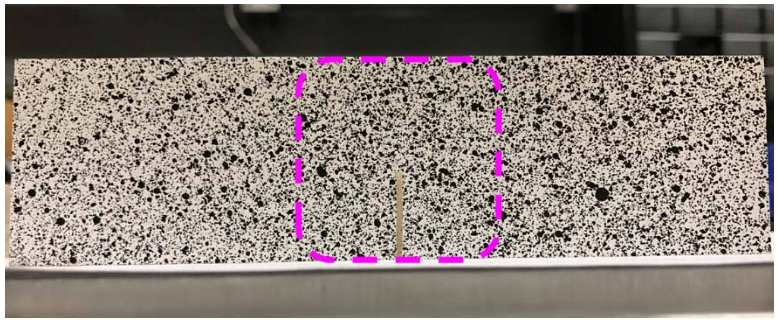

Figure 3: PMMA beam surface preparation for DIC

Toanalyze the imagesof impact process withGOM correlate software, a surface component was created at first. Emphasizing on the granularity of the sample, a surface component of 37 pixels was chosen, with a point distance of 18 pixels. The area of interest was also selected by using the Select/Deselect Polygon tool to include the crack propagation region. The original notch tip and the crack tip at each time step can be located in the images with GOM, the absolute crack propagation distances can then be directly extracted with GOM

III. Results and Discussions

a) Impact force on PMMA beam

The impact loadingswere extracted from the signals recorded with the load cell. The loading record resolution was set as 10μs.The force histories of impact processes with different impact velocities are presented in Fig. 4.In the figure, the impact force history at different impact velocities as v=1, 2, 3 m/sare presented separately with different marked curves.For impact with different velocities, similarly, the force curves initiate from zeroonce the impactor (loadcell) contact the top surface of the sample,and rise till the maximum values. The force then drops suddenly till even negative values, which indicate the loadcell recording of the reflection of the impact stress wave.However, the peak values of the impact force at different velocities are different. The peak force for impact at 3 m/s is the largest and 1 m/s thelowest. The crack initiates at the time of the peak impact force and propagates till the fracture, as shown in Fig. 5, Fig. 6, and Fig. 7.

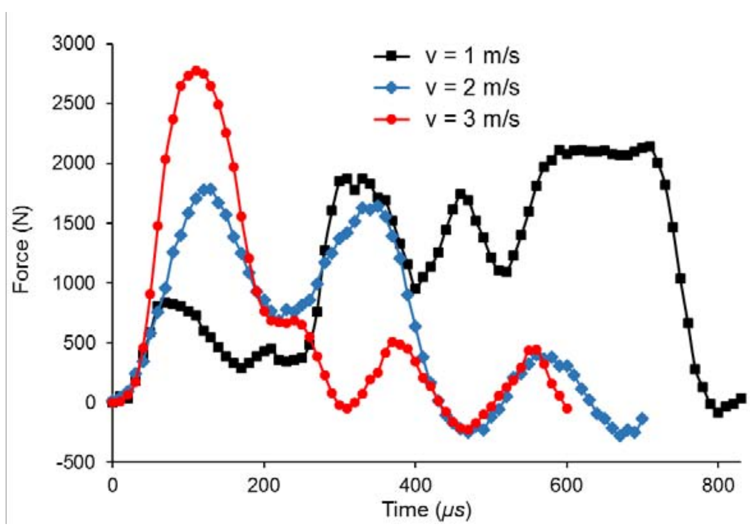

Figure 4: Force history of impact processes with different impact velocities

b) Impact fracture process

The impact fracture process in PMMA beam with the corresponding displacement fields have been presented in Fig. 5, Fig. 6, and Fig. 7, with the impact velocities at 1 m/s, 2 m/s, and 3 m/s respectively.In Fig. 5, the fracture initiates at 630 μs after the dropping weightcontacts the top surface of the PMMA beam, which means the loading time is 630 μs till the crack

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initiate from the tip of the original notch. The crack propagations from the initiation at 630 μs, to 690 μs, till 780 $\mu s$are presented in Fig. 5, with the crack tip marked with the white arrows. During the fracture process, as the crack length increases, both the displacements in x and y directions increase correspondingly. The detail displacement field contour can be found in Fig. 5 with the specific color bar. Displacements fields are symmetric to the vertical line of the original notch. The change of the color in the displacement contour indicates the deformation process of the beam during the impact process, which lasts as short as round 150 μs.

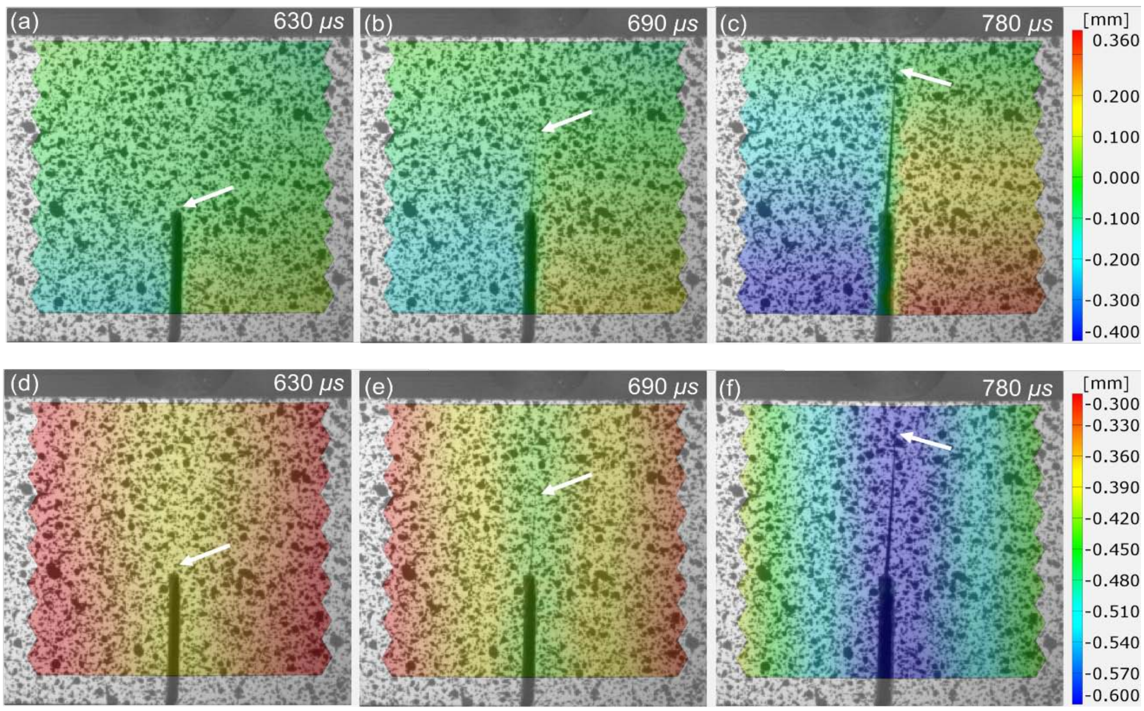

Figure 5: Crack initiation and propagation at different time steps, with the corresponding displacement fields (displacements in x direction: (a), (b), and (c); displacements in y direciton (d),(e), and (f))in the PMMA beam after the impact at the velocity of 1 m/s. (The crack tips are marked with the white arrows)

Once the dropping weight reaches the top surface of the beam, the beam is subjected to an impact loading and starts to bend due to the simply supported boundary conditions at the bottom surface. During the impact bending process, the tensile stress concentration increases at the tip of the original notch. The crack initiates to propagate once the stress intensity factor reaches the critical value (fracture toughness).

Fig. 6 shows the fracture process in PMMA beam with the impact at a velocity of 2 m/s. The fracture initiates at 285 μs after the dropping weight contacts the top surface of the PMMA beam. During that time, the dropping weight subject impact loading at the middle of the top surface of the beam, which causes the beam bending with the increase of the stress concentration at the crack top. The crack propagations from the initiation at 285 μs, to 345 μs, till 435 μs, with the crack tip marked with the white arrows in Fig. 6. Similar to the impact at a velocity of 1 m/s, during the fracture process, as the crack length increases, both displacements in x and y directions increase correspondingly. The detail displacement field contour with color bar can be found in Fig. 6. Displacements fields are also symmetric to the vertical line of the original notch. The change of the color in the displacement contour indicates the deformation process of the beam during the impact process, which lasts during the time period as short as about 150 μs.

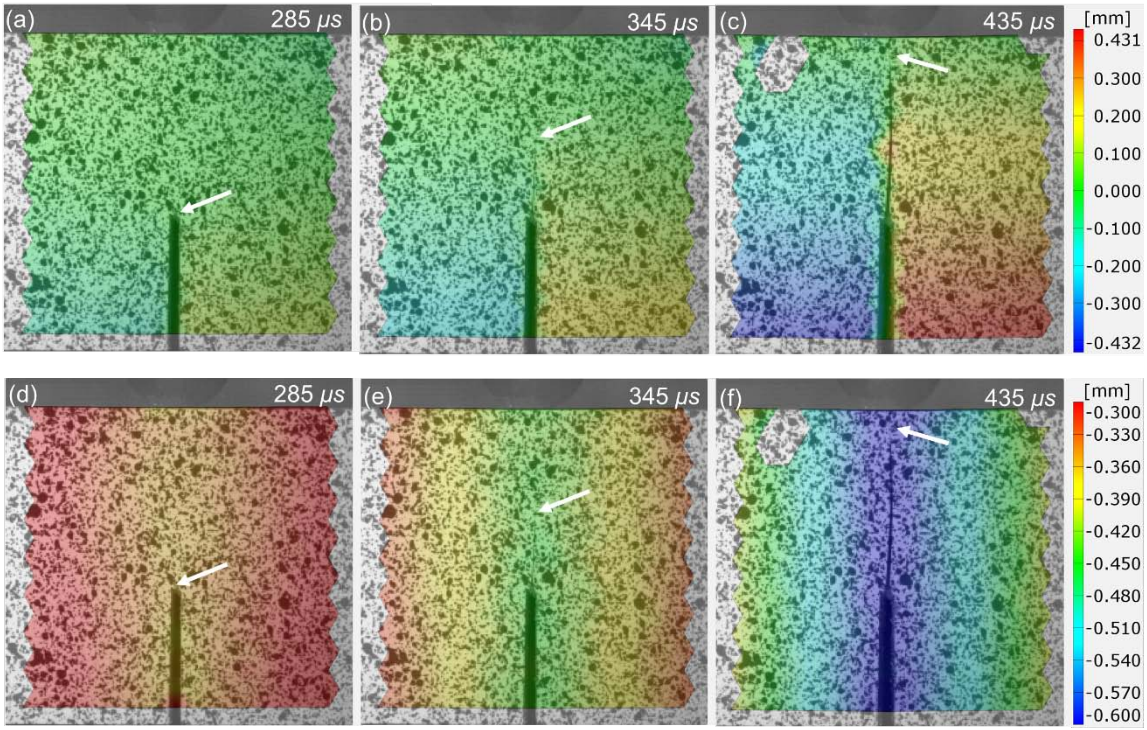

Figure 6: Crack initiation and propagation at different time steps, with the corresponding displacement fields (displacements in x direction: (a), (b), and (c); displacements in y direciton (d),(e), and (f))in the PMMA beam after the impact at the velocity of 2 m/s. (The crack tips are marked with the white arrows)

Fig. 7 shows the fracture process in the PMMA beam with the impact at a velocity of 3 m/s. The fracture initiates at 110 μs after the dropping weight contacts the top surface of the PMMA beam. The crack propagations from the initiation at 110 μs, to 170 μs, till 260 μs, with the crack tip marked with the arrows in Fig. 7. Similarly, during the fracture process, the crack length increases, and both the displacements in x and y directions increase correspondingly. The detail displacement field contour with color bar can be found in Fig. 7. Displacements fields are also symmetric to the vertical line of the original notch. The displacements contours indicate the deformation process of the beam during the impact process, which lasts during the time period as short as round 150 μs too.

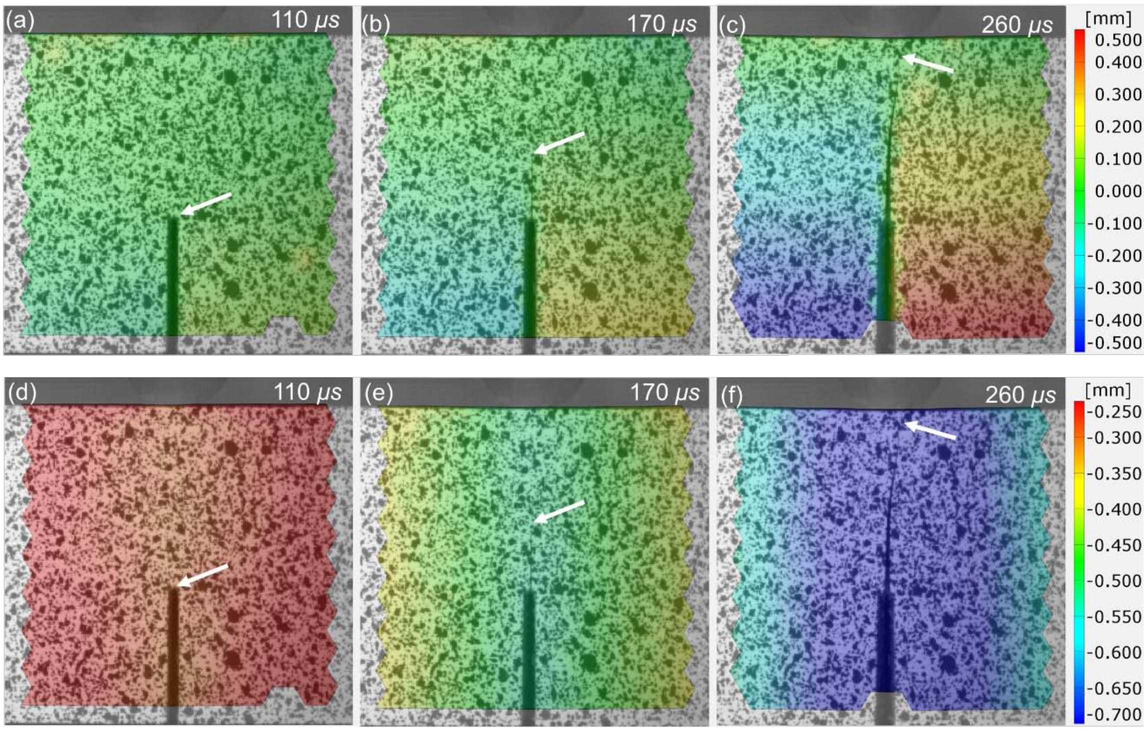

Figure 7: Crack initiation and propagation at different time steps, with the corresponding displacement fields (displacements in x direction: (a), (b), and (c); displacements in y direciton (d),(e), and (f))in the PMMA beam after the impact at the velocity of 3 m/s. (The crack tips are marked with the white arrows)

The crack initiation and propagation length history in PMMA beams subjected to impact at different impact velocities are shown inFig. 8. During the impact process, the time step when the dropping weight contacts the surface of the beam is set as 0. The crack initiation time for PMMA beam subjected to impact at velocities of 1 m/s, 2 m/s, and 3 m/s are 635 μs, to 265 μs, and 110 μs, respectively. Obviously, the loading time before the crack initiates is much longer for higher impact velocity, shorter for lower impact velocity. The cracks propagate till 20 *mm* within about 150 μs, but with adifferent slope of the length curves, which means the crack velocities are different, as shown inFig. 8.

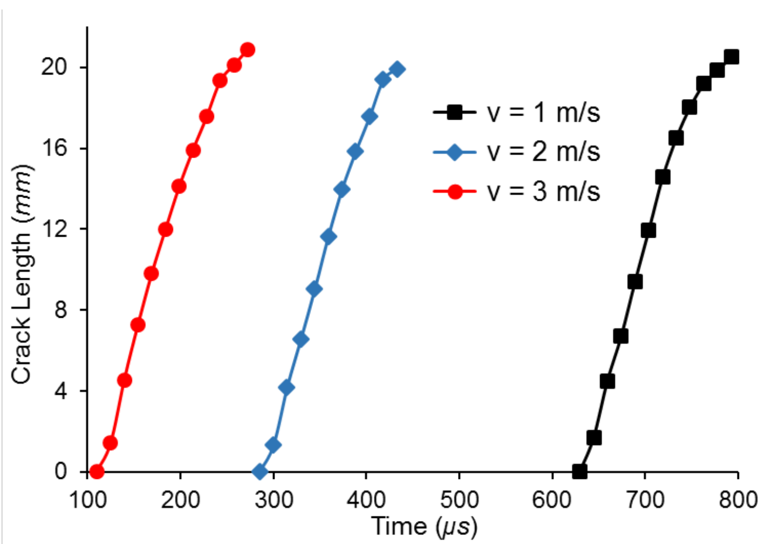

Figure 8: Crack initiation and propagation length history in PMMA beams subjected to impact with different impact velocities

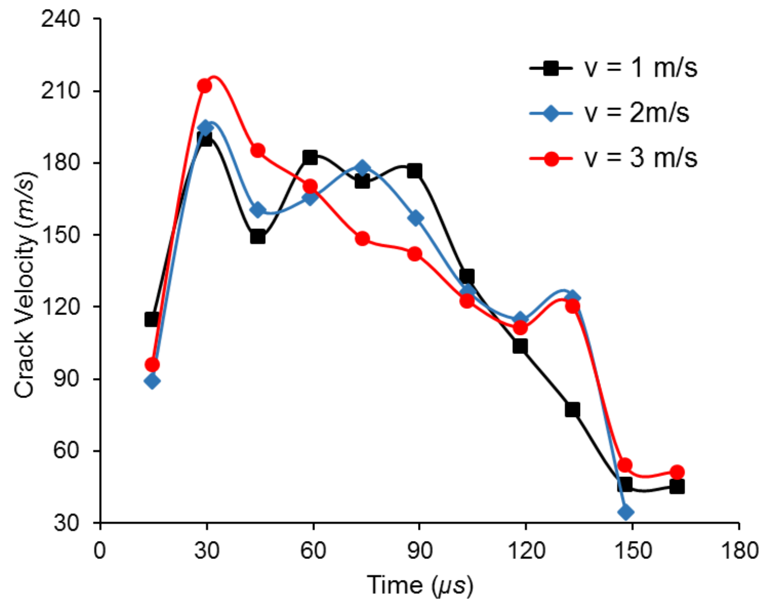

Figure 9: Crack speeds after crack initiation in PMMA beams subjected to impact with different impact velocities

The crack propagation speeds after crack initiation in PMMA beams subjected to impact with different impact velocities are shown inFig. 9, in which the time is set as 0 at the crack initiation point.The crack velocities in beams subjected to different impact loading have the similar trend. Crack velocities start from a relatively lowervalue round 100 m/s, then rise to the peak value round 200 m/s, and decrease till the fracture. The peak crack velocities for fracture in beams subjected to different impact are different. For fracture in the beam under theimpact of 3 m/s, the peak crack velocity is highest as 212 m/s. The peak crack velocities in thebeam under theimpact of 2 m/s and 1 m/s are lower as 195 m/s and 189 m/s respectively.

IV. Conclusion

The impact-induced dynamic fracture initiation and propagation in single-edge-notched PMMA beams have been analyzed in this paper. Crack initiates later after the contact of impact when it is subjected to smaller impact velocity. During the dynamic fracture process, crack velocities rise from a lower value, then reach the peak value, and then decrease till fracture. Peak velocity of the fracture in beam subjected to bigger impact loading is higher than that in the beam under smaller impact loading.

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