Experimental Investigation of Dynamic Fracture Initiation in PMMA Submerged in Water

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Abstract The mode-I dynamic fracture response of notched PMMA plates submerged in water was investigated. The experimental setup utilized was designed to study underwater crack propagation with the aid of visualization techniques to obtain quantitative and qualitative results. High-speed imaging and the method of transmitted caustics were used to complete the measurements. The main objective of this study was to determine the effect of surrounding water on the dynamic fracture behavior of samples as they were impacted. The properties measured to assess the effect of water were the stress intensity factor and crack speed in the initial stages of crack propagation. Experiments were also completed for samples surrounded by air for comparison purposes. Results showed that the presence of water had no effect on the fracture behavior of PMMA at strain rates of the order of 10^2 s^{-1} .

Keywords Underwater · Dynamic fracture · High-speed imaging · Impact loading · Caustics

Introduction

The study of fracture initiation in materials subjected to dynamic loading is necessary to estimate the allowable stresses that structures can withstand at high strain rates. However, an experimental study of structures subjected to extreme conditions, such as underwater dynamic loading, can be particularly challenging since the implementation of

visualization techniques and load characterization methods can be complicated compared to air environment experiments. In most cases, these events constitute situations involving significant fluid-solid interactions, which could threaten the integrity of structures and potentially lead to catastrophic failure. For instance, coastal buildings, ship hulls subjected to wave slamming, or submarines subjected to underwater explosions are scenarios where catastrophic failure can occur. Therefore, it is necessary to understand the fracture behavior of structures in underwater situations when subjected to dynamic loading conditions in order to improve future design considerations and minimize damage. The experiments were performed on Poly(methyl methacrylate) (PMMA). Even though not typically used as an underwater structural material, PMMA can be used for windows in submarines. PMMA is a well-characterized material whose dynamic fracture behavior has been studied for different fracture modes and loading conditions [1, 2]. PMMA was used in this work to develop the experimental setup and visualization technique for underwater conditions, as well as to understand its dynamic fracture behavior when submerged in water.

It is well known that the main factors that affect the fracture toughness of a material are the specimen dimensions, geometry, temperature, molecular weight, and loading rate. Furthermore, it has been discovered that the surrounding environment has an important role in the fracture behavior of a material [3]. Specifically, the effects of a liquid environment on a propagating crack have been studied for many types of materials and liquid environments subjected to quasi-static loading. Some of the most relevant studies and their findings will be briefly described in this section.

One of the first studies on the effect of liquid environments on fracture was performed on PMMA and inorganic

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glass by Williams and Marshall [4]. A fracture mechanics approach was used in conjunction with time-dependent material parameters to describe crack propagation in both air and liquid environments. A fluid flow model was inserted into crack propagation analysis to describe how failure processes were developed under different surrounding environments. This model was applied for crack speeds of up to 10^{-1} m/s and, among their results, it was stated that water causes plasticization of crack fronts.

Mai [5] performed an experimental study to examine continuous slow cracking of PMMA in the presence of a variety of liquid environments. Single-edge notched specimens were subjected to uniaxial loading at strain rates on the order of 10^{-3} – 10^{-2} s $^{-1}$. It was discovered that there is an increase in the energy required for fracture to occur in the presence of liquids, such as water, oils and alcohols, thus, plasticizing the crack-tip and increasing the toughness of the material. These results complement the findings by Williams and Marshall [4]. Additionally, it was discovered that the effect of water on fracture toughness is rate sensitive, which means that the effect of water on crack propagation was dependent on the crack-tip speed. Michalske and Frechette [6] conducted further studies to analyze the rate sensitivity of fracture toughness and proposed that for crack-tip speeds higher than 10^{-1} m/s, an accelerating crack is able to completely escape all effects of water. This behavior was attributed to the viscosity of the liquid, which does not allow the liquid to flow into the crack-tip fast enough. In other words, the moment the crack-tip speed is fast enough for it to escape the effect of the surrounding liquid, the fracture behavior of the material is the same as in air.

Additional studies have yielded similar results, which can be summarized in that, at low crack-tip speeds, fracture properties are drastically changed when a crack propagates while immersed in water. At low strain rates, the fracture toughness of PMMA increases to almost double that of the material in air due to the plasticization effect of water. The reason for this behavior is that the duration of the fracture event is longer, which allows more time for water to flow into the crack tip and promote plasticization. On the other hand, as the strain rate is increased, water does not seem to affect the fracture behavior of the material [7, 8].

Alternative mechanisms have been suggested to explain the effect of liquids on low-speed crack propagation. Among some of those mechanisms are surface tension, hydrogen bonding breakage or chemical interactions between the surrounding liquid and the polymer, and the absorption of some of the stored elastic strain energy by the liquid [3, 9–11]. Nevertheless, it seems that plasticization occurring on the crack-tip at strain rates lower than 10^{-2} s $^{-1}$ [10] or crack propagation speeds lower than 10^{-1} m/s [6, 10] prevails as the most accepted explanation

for the variation of fracture behavior of PMMA in the presence of water.

All the previously mentioned experiments have been performed for specimens subjected to quasi-static loading and resulting crack-tip speeds in the range of 3×10^{-5} to 2×10^{-1} m/s. Moreover, no studies were found in the literature for materials subjected to dynamic loading when exposed to a liquid environment. The main difference between quasi-static fracture and dynamic fracture is the presence of stress waves in the latter. The stress waves generate crack initiation and propagation if the stress amplitude overcomes the dynamic fracture toughness of the material [12, 13].

Dynamic fracture toughness is defined as the minimum stress intensity factor (SIF) required to initiate crack propagation, also referred to as the critical SIF. Under dynamic loading, the critical SIF is higher than the quasi-static fracture toughness. Ravi-Chandar and Knauss [14] proposed that the critical SIF grows with increasing strain rate for dynamic loading conditions because there is an intrinsic time associated with the nucleation and growth of cracking processes. Thus, if the rate of loading is smaller than the rate of microprocesses, quasi-static results would be obtained and the stress intensity factor would remain constant. Conversely, if the loading rate is increased to dynamic loading conditions, the microscopic processes would not be fully developed, leading to a tolerance for higher loads. In other words, when crack-tips are subjected to dynamic loading rates or shorter stress pulses, the stress intensity factor of the material increases monotonically, allowing the material to withstand higher loads before the crack propagates.

There exists a general understanding of the effect of surrounding water on polymer fracture for quasi-static loading and low-speed crack propagation. Nevertheless, most of the studies have used simple fracture tests to quantify the effects of surrounding liquids, and real-time crack-tip behavior under extreme environmental conditions has been much less studied [8]. An extension of these studies to higher strain rates could possibly identify other mechanisms that may affect the dynamic fracture behavior of a material since it is well known that the mechanical response of PMMA changes when it is subjected to dynamic loading. For this reason, in this study, crack initiation in PMMA immersed in water when subjected to an impact were investigated. These experiments were executed to observe if there is any sort of coupling between the surrounding fluid and the solid during the impact event that would affect the dynamic behavior of cracks propagating underwater, e.g., surface energy dissipation into the surrounding water may arise due to higher strain rate. To the best of the authors' knowledge, there have been no previous experimental studies utilizing high-speed visualization

to measure in-situ fracture initiation when the material has been subjected to strain rates in the orders of 10^2 s^{-1} . The optical method of transmitted caustics with high-speed imaging and simultaneous strain gauge measurements were utilized in these experiments. These experiments quantified the fracture behavior of PMMA, and the SIF and crack-tip speeds were compared for cracks initiated in air and water.

Methods and Material

To simulate dynamic loading conditions on structures immersed in a water environment, an impact was generated using a 10 mm diameter spherical steel projectile launched onto rectangular PMMA notched samples with mid-sections immersed in water.

Experimental Procedure

Commercially available PMMA (from Emco Industrial Plastics, Inc) was used to make the samples for these experiments. The geometry of these samples with dimensions $300 \times 40 \times 3.125 \text{ mm}^3$, similar to the ones utilized by Theocaris and Katsamanis [1, 15, 16], was chosen to obtain mode-I crack propagation during impact. The impact was generated with a spherical projectile to cause a point load, which is convenient for these experiments due to the small thickness of the samples. Once the projectile impinged on the edge of the sample, a compressive pulse travelled down the length of the specimen and reflected back from its free end as a tensile pulse. By applying a point load, the length of the pulse was controlled such that there was no interaction between the compressive and tensile pulse in the vicinity of the crack-tip. When the tensile pulse reached the notch, it promoted mode-I fracture if the stress amplitude of the pulse was sufficiently high [17]. Figure 1 shows the geometry of the sample. The design of this sample was such that plane stress was assumed [1]. Prior to each experiment, one strain gauge was installed on each sample. These gauges were attached at the mid-height of the sample, 50 mm behind the notch as

Fig. 1 Sample geometry. The field of view of the camera is indicated and the sample's appearance through the camera is shown (Resolution: $78 \mu\text{m}/\text{pixel}$)

seen from the impact direction, to measure the strain response of the material.

The setup utilized for these experiments consists of a pressurized gas gun, a visualization system, and a catcher box to contain the specimens during and after impact. Further details about this setup and launching mechanism are provided in [16]. Here, a Phantom V711 high-speed camera was synchronized with a pulsed laser (SONY SLD1223V 670 nm laser diode combined with PicoLAS LDP-V drive module) used as a light source. The high-speed camera was set to record at a frame rate of 80,000 frames per second, which resulted in a time interval of $12.62 \mu\text{s}$ between consecutive images and a resolution of 256×256 pixels. The exposure time was set to 90 ns. Figure 1 shows the field of view of the camera that corresponded to a $20 \times 20 \text{ mm}^2$ section of the sample, resulting in a scaling factor of $78 \mu\text{m}$ per pixel. Optical distortions resulting from the visualization system were removed using the control point selection toolbox in MATLAB as described in [15].

One of the main challenges that arose while performing these experiments was to obtain repeatable central edge-on impacts onto the samples to compare the results from consecutive experiments. For this reason, an alignment setup, contained inside the catcher box, was designed such that samples were aligned with the longitudinal axis of the gun barrel (the direction of impact). A schematic drawing of the apparatus utilized to generate dynamic loading conditions is featured in Fig. 2. The setup consisted of two aluminum stands, two 600 mm long alignment pins, and a stainless-steel test section. The front aluminum stand, which was clamped onto the end of the gun barrel, and the rear stand (not shown in Fig. 2),

Fig. 2 Impact schematic. The setup consists of: (1) Gun barrel, (2) Front aluminum stand, (3) Sabot utilized to carry projectile inside of gun barrel during launch, and the sabot was mechanically stopped as it exited the barrel (mechanism not shown in this schematic), (4) 10 mm diameter stainless steel sphere projectile, (5) Alignment pin, (6) Stainless-steel test section positioning sample in place

were both bolted onto an optical table. The stands included two holes located (vertically) above and below of the gun barrel, aligned with the barrel's centerline. The two alignment pins were inserted into the holes to create a rail system used to properly align the test section in front of the exit of the gun, as shown in Fig. 2. An exploded view of the test section is shown in Fig. 3 to illustrate its features in detail. The test section comprises an assembly of a stainless steel frame and two acrylic side windows to allow for light transmission. Additionally, the test section has the capability of containing liquids in the volume encapsulated by the windows and the frame. O-rings were included as part of the assembly to create a seal between components of the test section and avoid water leakage at the interfaces. The water supply was fed into the test section through a small orifice located on its top surface. The water was supplied through a thin hose that connected the test section to the top of the catcher box, where a small water-filled reservoir was placed. The experimental samples were inserted into the test section as

Fig. 3 Exploded view of test section: (1) Window, (2) O-ring to prevent water leakage, (3) Frame insert to secure sample, (4) Sample, (5) Holder frame

shown in Fig. 2 allowing the middle part of the specimen, containing the notch, to be immersed in water. Note that during the experiments, samples were allowed to move in the longitudinal direction to avoid introducing complex boundary conditions. For this to occur, it was required that there was no tight seal in the gap through which the samples were inserted into the frame. Thus, water was allowed to leak through the interface between the test section and the specimens. In order to maintain the test section filled with water for the duration of the experiment, a constant feed of water was provided from the reservoir. Once the samples were placed in the test section and immersed in water, the specimens were surrounded by 5 mm of water on each of its sides.

Method of Caustics in Liquid Media

The method of caustics was applied in compliance with the guidelines outlined in [18]. The method of caustics is suitable for these experiments because it allows visualization of crack propagation in transparent media, such as air or water, which was used to quantify the SIF and crack-tip speed of PMMA. The principles of this method have been described in detail elsewhere [19], so only relevant equations and values used for data analysis will be presented.

Equation (1) is applied to calculate the SIF [19]. The SIF, K_I , is expressed as a function of the transverse diameter of the caustic, D , the sample thickness, t , the crack-tip speed, v , the longitudinal and transverse wave speed, c_L and c_T , respectively, as well as other experimental setup constants and material properties shown in Table 1,

$$K_I = \frac{2\sqrt{2\pi}F(v)}{3m^{3/2}ctz_0} \left(\frac{D}{3.17} \right)^{5/2} \quad (1)$$

where,

Table 1 Experimental constants and material properties used for the method of caustics

	Notation	Value	Unit
Distance to reference plane	z_0	1.4	m
Scale factor	m	1.01	–
Stress optical coefficient in air	c	-5.50×10^{-11}	m^2/N
Stress optical coefficient in water	c	-4.01×10^{-11}	m^2/N
Longitudinal wave speed ^a	c_L	2750	m/s
Transverse wave speed ^a	c_T	1500	m/s
Density	ρ	1180	kg/m^3
Poisson's ratio	ν	0.35	–
PMMA constant ^b	b	–0.557	–

^a Measured using an ultrasonic thickness gage (Olympus 38DL PLUS)

^b Value obtained from [23]

Fig. 4 Comparison of caustic size for samples surrounded by air and water using the same optical setup

$$F(v) = \frac{4\alpha_1\alpha_2 - (1 + \alpha_2^2)^2}{(\alpha_1^2 - \alpha_2^2)(1 + \alpha_2^2)},$$

$$\alpha_1 = \left(1 - \frac{v^2}{c_L^2}\right)^{\frac{1}{2}},$$

$$\alpha_2 = \left(1 - \frac{v^2}{c_T^2}\right)^{\frac{1}{2}}.$$

The presence of water will cause an optical effect that reduces the size of the caustic curve. Abo-El-Ezz et al. [20, 21] were the first ones to observe this optical effect when the method of caustics was applied to investigate the crack growth of PMMA submerged in water and methanol while subjected to uniaxial loads. In these studies, a change in the diameter of the caustic curves surrounded by water was observed when compared to caustic curves in air subjected to the same loading conditions. The change in diameter occurs because the refractive index of water, $n = 1.33$, is in between that of air, $n = 1$, and of PMMA, $n = 1.49$. Therefore, when a propagating crack is immersed in water, the light ray deviation angle is smaller than in air after refraction, which generates a smaller caustic curve [22].

Figure 4 shows images obtained in this study for samples subjected to the same dynamic loading conditions in air and water. The images are taken at the moment prior to crack growth in each experiment; thus, it is assumed that the transverse diameter of the caustic should be of the same of the length. However, as it can be seen, the transverse diameter of the caustic in water is smaller than the one in air.

For this reason, an adjustment was applied to the analysis of the SIF. The variation in the length of the transverse diameter of the caustic was taken into consideration by estimating a different value of the stress optical coefficient (SOC) of the sample to account for the surrounding water. Equation (2) was used to estimate the SOC of PMMA submerged in water [23]

$$c = \frac{1}{E}[(1 - 2\nu)(1 + \nu k)b + (n - n_0)\nu(k - 1)] \quad (2)$$

where b is a material constant ($b = -0.557$ for PMMA [23]), n is the index of refraction of the material, n_0 is the index of refraction of the liquid medium surrounding the specimen (water with $n_0 = 1.33$), and ν is Poisson's ratio. The k value is a measurement of the three-dimensionality of the state of stress applied with a range between the values of 0 and 1 for plane stress and plane strain, respectively. Here, the loading condition is considered to be plane stress, so $k = 0$. By making this assumption, Eq. (2) simplifies to

$$c = \frac{1}{E}[b(1 - 2\nu) - \nu(n - n_0)]. \quad (3)$$

Equation (4) was used to quantify the dynamic elastic modulus of PMMA to be used in the calculation of its SOC

$$E = \frac{c_L^2 \rho (1 - \nu)}{(1 + \nu)(1 - 2\nu)} \quad (4)$$

The value obtained for the dynamic elastic modulus of PMMA was $E = 5.56$ GPa, which is similar to the value, $E = 5.60$ GPa, reported by [24]. Finally, the experimental constants and material properties used for the analysis of the results from the method of caustics are shown in Table 1. Note that due to the many assumptions taken to obtain Eq. (3), the SOC values utilized in the present work are estimates only.

Results and Discussion

The results reported next concern fracture initiation and early stages of crack propagation in PMMA surrounded by air and water. Prior to the impact experiments, all samples were treated for 24 h at 76 °C to remove any moisture content and establish equal initial conditions. All results regarding crack propagation in air correspond to data reproduced from [15] in which the same experimental setup was used. Figure 5 shows a sequence of caustic images exemplifying the footage obtained from these

Fig. 5 Crack propagation sequence for a sample immersed in water. Images show area of interest ($20 \times 20 \text{ mm}^2$) as indicated in Fig. 1 and corresponding caustic diameters, D , are presented in the sub-captions of each frame

experiments. Each of these images were post-processed to measure the transverse diameter of the caustic and to obtain the crack-tip location. An average of 5 frames were analyzed for each experiment.

The repeatability of the loading conditions was interpreted by comparing the impact speed for each experiment, and the strain response obtained from the strain gauges attached to each sample. The impact speed was measured using a velocity sensor attached to the exit of the gun barrel. As the projectile passed by this sensor, a square wave was generated. The pulse duration of the square wave, Δt , represents the time it took the sabot to travel through the sensor; thus, Δt combined with the known length of the sabot was utilized to calculate the impact speed. The projectile speed used for these experiments was $37.83 \pm 0.4 \text{ m/s}$ and $38.83 \pm 1.1 \text{ m/s}$ for experiments in air and water, respectively. At this impact speed, stress waves with a pulse duration of approximately $70 \mu\text{s}$ were generated in the samples.

The average strain response obtained for a total of eight samples exposed to either environments is shown in Fig. 6. From these results it was calculated that the samples were subjected to a strain rate of approximately 10^2 s^{-1} . Overall, the strain responses for both cases are similar and follow the same behavior, a compression pulse followed by a tension pulse. Still, as it can be seen in Fig. 6, it appears that the addition of water on the surroundings of the specimens had a dampening effect on the amplitude of the reflected tensile pulse. The strain response of the samples

Fig. 6 Average strain response comparison of four samples per case

exposed to air exhibit a stronger nonlinear behavior, which could be attributed to high-frequency vibrations within the structure picked up by the strain gauge. Contrastingly, these vibrations may not occur when water is present as the density of water, which is significantly higher than the density of air, might not allow it.

Figure 7 shows a comparison of the crack-tip speed of a total of eight samples that were subjected to dynamic loading with their notch surrounded by either air or water. These results reveal that samples surrounded by water show no significant effect on the initial stages of the crack-tip speed of PMMA. Figure 8 shows a comparison of the SIF measurements obtained for cracks propagating in air and water. It is clear that the presence of water has no effect on the fracture toughness or SIF of this material,

Fig. 7 Crack-tip speed corresponding to four samples exposed to air (circle) [15] and four samples exposed to water (black triangle). Uncertainty for each data point is represented by marker size

Fig. 8 Stress Intensity Factor corresponding to four samples exposed to air (circle [15]) and four samples exposed to water (black triangle) for the early stages of crack growth. Uncertainty for each data point is represented by marker size

as both scenarios show a clearly defined critical SIF ($\sim 2 \text{ MPa}\sqrt{\text{m}}$), interpreted as the instant when the crack starts propagating. Additionally, it can be seen that the SIF for propagating cracks submerged in water was 10 % higher than the SIF for cracks propagating in air. This variation in the SIF can be attributed to the use of Eq. (3), as it only calculates an estimate value of the SOC, which could have introduced a rough approximation of the SIF. Nevertheless, if Eq. (3) was not utilized in the analysis of this experiments there would be a 35 % difference in the SIF values between cracks propagating in air and water. In any case, it is likely that the 10 % increment in the SIF was not caused due to plasticization generated from water exposure. The reason for this suggestion is because of the results presented in Fig. 7, which showed no difference in the crack-tip speed between both cases. The crack-tip speed measurements were not affected by an estimated value and were directly measured from the footage obtained during the experiments. Thus, if the crack-tip speeds showed the same behavior and the SIF presented

similar values for both cases, it is proposed that surrounding water does not significantly alter the dynamic fracture behavior of PMMA.

In this work, it was initially proposed that at high loading rates, a coupling effect between the structure and surrounding liquid may result in a variation of dynamic fracture of the material. However, even though a small difference in the strain response was captured by the strain gauges, namely a dampening effect on the amplitude of the tensile pulse exemplified in Fig. 6, no significant effect on the fracture behavior of the samples was observed. These findings partially agree with previously reported results in which surrounding water showed no effect on cracks propagating faster than 10^{-1} m/s . These studies indicated that at some point the crack-tip speed was too fast for the liquid to diffuse into the crack-tip and plasticize it. On the other hand, the inability of a liquid to diffuse into a propagating crack does not explain why no plasticizing effect was observed on the notch before crack initiation occurred. Prior to the crack initiation stage, there was sufficient time for surrounding water to plasticize the crack tip, yet the fracture behavior was the same as in air. Therefore, it is suggested that plasticization did occur prior to the fracture event, but the effect of the strain rate, which also increases the fracture toughness of the material, dominated the fracture behavior of the material, resulting in similar results for both environments studied. An analytical model to predict the results obtained here is beyond the present scope of this work but will be addressed in future studies.

Conclusions

An experimental investigation on underwater dynamic fracture initiation of PMMA was completed. To the best of the authors' knowledge, this constitutes the first study in which dynamic underwater crack propagation is observed and quantitative data is obtained using visualization techniques. The stress intensity factor and crack-tip speeds were measured using the method of caustics coupled with high-speed photography. Results showed that water media has no significant effect on the dynamic fracture initiation of the material when it is subjected to an impact resulting in strain rates of 10^2 s^{-1} . It was initially proposed that other influencing mechanisms on underwater crack propagation, such as surface energy dissipation into the surrounding water, may arise due to higher strain rate. However, no significant variation was observed in the analysis of the crack tip speed or SIF. Results also imply that the mechanism that prevented water from having an effect on the crack propagation of PMMA subjected to low strain rates prevails at the higher

strain rates studied here (up to 10^2 s^{-1}). Moreover, since the notch of the samples was static prior to crack initiation, it was proposed that water does plasticize the crack tip before fracture occurs, but strain rate effects overcome any effect that water induced. Thus, strain rate seems to dominate the fracture event by overcoming the plasticizing mechanism prior to crack initiation and by generating fast crack-tip speeds that do not allow water to diffuse into the propagating crack.

Clearly, the aim of this study has been to demonstrate the experimental capabilities available to determine the dynamic fracture of transparent materials underwater. The main limitation in the present work are the assumptions taken to overcome the optical effect that water causes. More accurate results could be obtained if a more robust visualization technique, such as digital image correlation (DIC), could be implemented to quantify the dynamic fracture of materials submerged in water. The use of DIC will require higher temporal and spatial resolution, which can be resolved by using ultra high-speed cameras. While beyond the scope of this work, the aforementioned discussion is part of an ongoing effort to continue the study of dynamic fracture in extreme environments and to contribute to the experimental mechanics community.

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