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Fracture Behavior of RT-PMMA Under Impact Loading

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Abstract: Fracture mechanism of polymer under high strain rate loading is still today a complicated issue in developing their design as protection structure. In this paper, we aim to investigate the crack arrest capability of RT-PMMA when subjected to impact loading. For that purpose, Kalthoff and Winkler (KW)-like impact tests are performed using the STIMPACT platform gas launchers. Double notched specimens were impacted on the edge within a range of impact velocities (50-140 m/s). During the investigation, the failure mechanism is recorded by a high speed camera. The stress whitening phenomena is explained and it is shown that addition of rubber to PMMA matrix aids to enhance its impact toughness. This involves energy dissipation by the rubber and higher energy required for crack propagation in rubber toughened RT-PMMA as compared in neat PMMA. High impact velocities promote greater effect proved by large number of fragments produced aftermath. By carrying out uniaxial tensile tests, it was established that the mechanical behaviour of RT-PMMA strongly depends on strain rate and temperature.

Keywords: Impact, fragmentation, RT-PMMA

1. Introduction

Amorphous polymers such as Polycarbonate (PC), Polystyrene (PS) and Polymethylmethacrylate (PMMA) have been widely applied in engineering applications regarding their lightweight, transparency and ease of processing [1]. It is made of acrylic and have high transparency [2]. By having property similar to glass, it has proven to be a good alternative to be used in diverse industries of national production such as aircraft windshield and porthole, radar screen, optical lenses of telescope, protecting cover of instrument, and also in automotive as well as armor related applications [2-4].

However, brittleness is one of the issues to be accounted for when dealing with PMMA. In order to protect all the structures using PMMA, several attempts were made to increase this property. An approach of blending small rubber particles in PMMA has been shown to improve the fracture and impact toughness of PMMA. This mixture is called as rubber toughened PMMA (RT-PMMA) [3]. A rubbery phase was introduced in order to increase energy dissipation in PMMA. With the optimum composition ratio and suitable rubber particle size, this will ensure a significant improvement in impact resistance while preserving the optical properties.[5–7].

Toughening mechanisms involved in most of the rubber toughened polymers can be described based on the concept of the energy release rate during fracture. Toughening can be achieved by introducing particles, including liquid rubber, thermoplastics, copolymer, nanoparticles, core shell particles and combination of these [9]. During fracture of RT-PMMA, rubber particles in the vicinity of the crack-tip deform and fracture, accompanied by crazing or shear yielding in the nearby matrix. As a result, energy needed for the crack propagation is greater than in the neat resins. Toughness mechanism is known to be affected by the constituent, structure, size and content of rubber particles, that further complicate the understanding of toughening mechanism involved [10]. The role of toughening mechanism that occurs in rubber-modified plastics, RT-PMMA in the present case, is to dissipate strain energy that are able to extend an existing flow or crack [11].

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Application of RT-PMMA in aeronautics, aerospace and automotive industry made it exposed to a wide range of loading involving various strain rates and temperatures. In this context, the present paper reports an experimental investigation carried out on RT-PMMA at high strain rate using Kalthoff and Winkler (KW)-like impact tests. A double notched plate was impacted on the edge in order to study the failure of RT-PMMA and its dynamic crack arrest capability. High speed camera is used to record the chronology of the failure mechanisms. A brittle failure was examined in the impact test and appearance of stress whitening evidenced the particle-matrix de-bonding mechanism of rubber particles and the PMMA.

2. Methodology

In this study, a highly transparent PMMA, Plexiglass Resist® in the form of a plate was used. A uniaxial tensile experiment was carried out using an Instron machine with a maximum capacity of 100 kN. A series of experiment was carried out at various strain rates (10^{-2}-10^{-4}) and temperatures (-10°C until 70°C). Experimental conditions at low and high temperatures were carried out with the aid of liquid nitrogen or in a furnace attached to the machine, respectively. For the impact tests, specimens were prepared according to the method of Kalthoff and Winkler (KW) where two notches reproduce pre cracks in the specimens. Impact loading experiments were performed at the Institut Clément Ader Lab using gas launchers STIMPACT platform. Various velocities were used, ranging between 50 and 140 m/s. The plate dimensions are $40 \times 82 \times 6$ mm^3 with notches of 300 µm-thickness and 20 mm-length. A 6 m-length gas launcher is used to launch a 20 mm-diameter cylindrical steel projectile. A Photron SA5 high-speed camera is used to observe the projectile/plate interaction at 10^5 fps (frame per second) and 320×192 pixel^2 spatial resolution.

3. Results and Discussion

Fig.1 (a) summarizes the tensile stress-strain curves of RT-PMMA over a strain rate of 10^{-2} to 10^{-4}. Mechanical behavior of PMMA in tensile tests exhibited an initial elastic response followed by yielding, strain softening and, finally, non-linear strain hardening. The specimens fracture in a brittle manner at high strain rate. In contrast, specimens failed in a ductile manner at low strain rate. Effect of temperature to the mechanical behaviour of RT-PMMA can be observed in Fig.2. As the temperature increases, the stress strain curves of PMMA changes significantly. This shows the strong dependence of mechanical properties of RT-PMMA on strain rate and temperature. Specimens under tension loading also experienced changes of appearance from transparent to nearly opaque (white) as in [6][12] which is known as stress whitening phenomenon.

During the impact tests, the fracture of the specimens was monitored by a high speed camera and some frames are shown in Fig. 3. The frames correspond to various impact velocities and have been recorded at the same time after the impact. Fig.3 depicts how the cracks initiate and propagate throughout the specimen. When reaching certain times, cracks that initiate from both notches start to propagate symmetrically with an initial angle close to 70° which is a typical for brittle failure [8]. This is also followed by a stress whitening zone that appear near the vicinity of the crack tip. Within few microseconds, another white zone starts to appear at the rear edge of the specimen where secondary cracks form. At high velocity, cracks were then propagating further and crack branching occurs resulting in the multi fragmentation of the specimen.

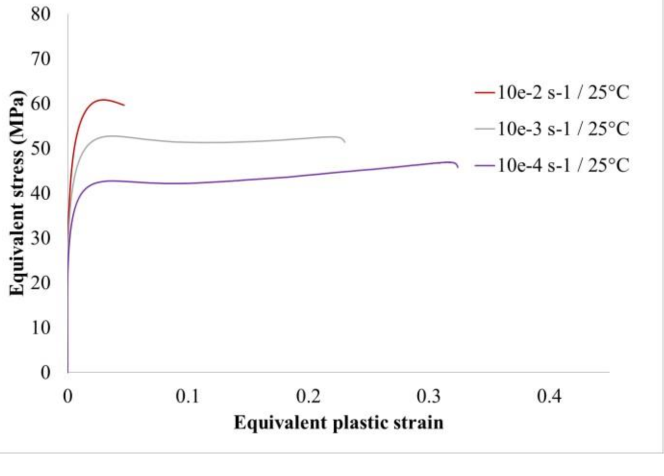

Fig. 1 - Stress strain curve of RT-PMMA at various strain rates and at room temperature

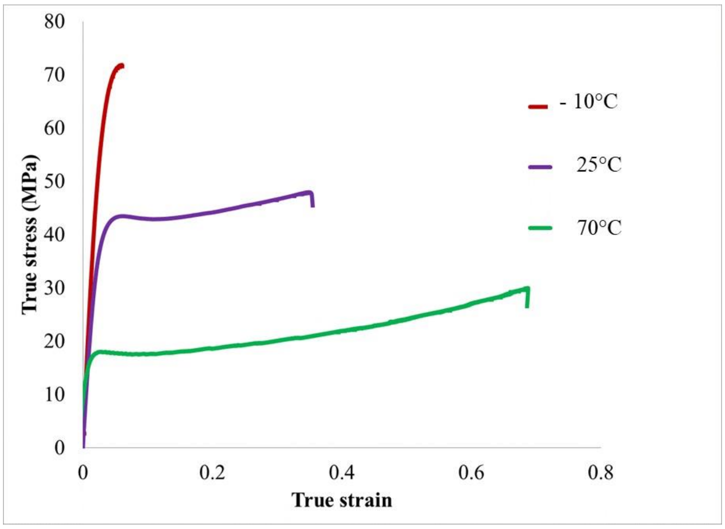

Fig. 2 - Stress strain curve of RT-PMMA at various temperature and at strain rate of 10^{-2} s^{-1}

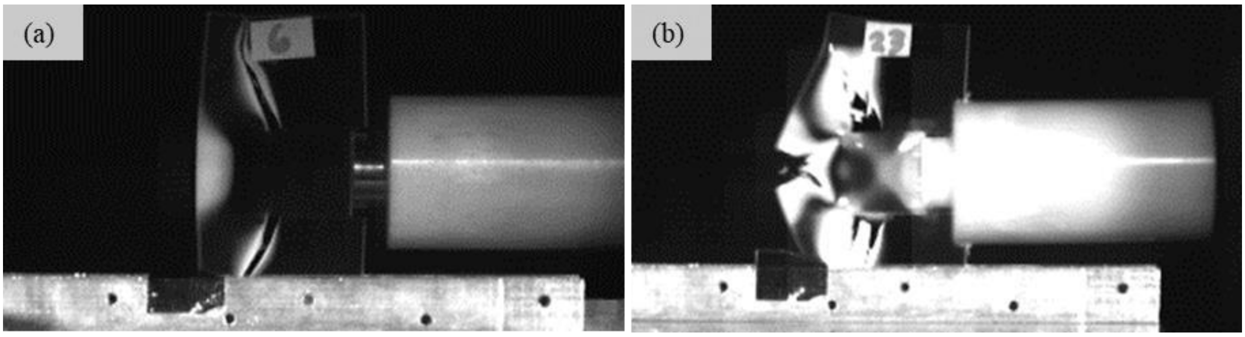

Fig. 3 - Images from high speed camera (a) during impact test at 50 m/s (b) during impact test at 140 m/s

RT-PMMA plates impacted at 140 m/s are damaged giving rise to many fragments of varying sizes. In contrast, for 50 and 80 m/s (not shown here), only a few large fragments were produced (see Fig. 4).

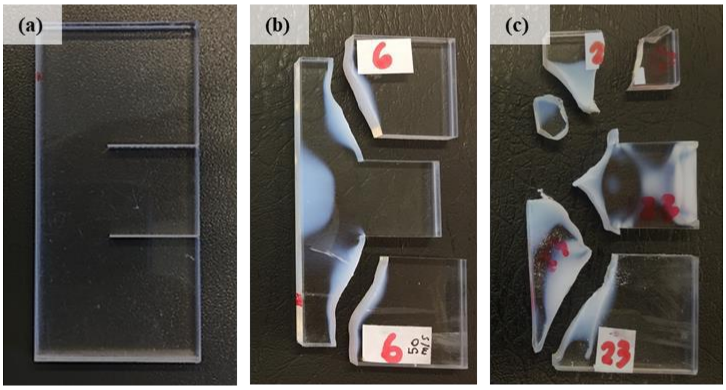

Fig. - KW-type specimens of RT-PMMA (a) before impact test; (b) after impact test at 50 m/s; (c) after impact test at 140 m/s

Stress whitening can be explained as a phenomenon which occurs when a transparent polymer is subjected to a tension or impact loading. During loading, a white stain or white zone appears on the specimen which is assumed to result from particles-matrix de-bonding. This creates microvoids that affects the light scattering of the material. This light scattering is the reason why the material appears to be transparent or opaque. However, according to the frames recorded using the high-speed camera, this stress whitening phenomenon seems to be reversible. It can be seen that the transparency of RT-PMMA is recovered probably due to the gap closure between the particle and matrix after de-bonding. This is not to be confused by the chemical bonding recovery of the rubber particles and PMMA matrix.

4. Conclusion

Based on the tension testing of RT-PMMA at different strain rate and temperature, its mechanical properties are strongly dependent on these two parameters. The Young Modulus is seen to be increasing with increasing strain rate and decreasing temperature. Higher impact velocity yields larger number of fragments produced after the impact test showing the impact velocity affects the toughness of RT-PMMA. However, the impact toughness of RT-PMMA is higher as compared to commercial neat PMMA (not shown here). This results from the the presence of rubber particles which help to dissipate energy during shock loading.

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