International Journal of Impact Engineering 38 (2011) 804–814

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Experimentation and modeling of inclined ballistic impact in thick polycarbonate plates

A. Dorogoy [a,*], D. Rittel [a], A. Brill [b]

[a] Faculty of Mechanical Engineering, Technion – Israel Institute of Technology, 32000 Haifa, Israel
[b] RAFAEL, P.O. Box 2250, Haifa, Israel

ARTICLE INFO

Article history:
Received 28 July 2010
Received in revised form
26 April 2011
Accepted 2 May 2011
Available online 10 May 2011

Keywords:
Inclined impact
Polycarbonate
Ricochet
Trajectory
Simulation

ABSTRACT

The penetration and perforation of a thick polycarbonate (PC) plate (one and 3 stacked) by an armor piercing 7.62 mm projectile is investigated experimentally and numerically. The characteristic structure of the projectile's trajectory in the PC plates is studied. It is observed that the trajectory consist of a cavity and a circumferential cracked zone attached to it, which is fully embedded within a cylindrical plastic zone. The size of the plastic zone is approximately twice that of the cavity zone and can be clearly observed due to the change of the refractive properties of the material. Strong local recovery of the PC is shown as well.

A 3D transient non-linear adiabatic finite element simulation is performed using the commercial software Abaqus 6.9-EF1. The numerical analyses include two combined failure criteria: "Ductile failure with damage evolution", and tensile failure. The material properties are strain rate and temperature dependent. The numerical simulations are tested by comparing the numerical trajectory prediction to actual trajectories of inclined impacts of projectiles. It is found that the projectile perforates the plate at angles of inclinations of 30° and higher. The observed agreement between experiments and numerical modeling indicates that the combined effect of the two failure criteria (tensile vs. ductile failure) can reasonably well predict the projectile's trajectory within a thick PC plate.

The numerical analyses are further used to study the effect of the projectile impact velocity on the depth of penetration (DOP). It is found that the DOP scales slightly non-linear with the impact velocity. The core velocity during the penetration process is also slightly non-linear. The deceleration during penetration is almost a linear function of the penetration velocity and it is higher for higher penetration velocities.

1. Introduction

Transparent polycarbonate (PC) is well known for its high ballistic resistance to penetration and perforation, and is widely used in impact-resistant applications. Hence numerous investigations have been carried out to characterize its static and dynamic flow and failure properties (e.g. Ravi-Chandar [1], Rittel et al. [2–6] and Sarva et al. [7]). Concerning its penetration behavior, quasi static deep penetration tests using circular cylindrical hardened steel punches were conducted by Wright et al. [8]. These authors noticed that the plastic zone diameter equals 3.5 times the punch diameter, and that the refractive index of PC changes markedly at yield. They also showed a damaged zone containing small cracks fully contained within the plastic zone which extends over 1.4 times the punch diameter. The resistance of thin PC plates (2, 5 and 12 mm) to impact by round and cylindrical projectiles was investigated experimentally by Wright et al. [9] who identified five main types of plate behavior: elastic dishing, petalling, deep penetration, cone cracking and plugging. Inclined impact on thin PC plates (less than 6.4 mm thick) was also investigated by Li and Goldsmith [10], who noticed that the resulting perforation hole exhibits a much smaller diameter than the projectile, indicating a substantial capability for recovery. The ballistic resistance of clamped thin PC plates to single [11] and multiple ballistic impacts [12] was investigated as well. It was concluded that reinforcements should be provided near the clamped edges.

Following Rosenberg et al. [13], a study was conducted on inclined impact of polymethylmethacrylate (PMMA) thick plates [14] in which the combined effects of brittle (spalling) and ductile failure mechanism were included. Such an investigation has not yet been carried out on thick polycarbonate plates. Hence, this investigation addresses the inclined ballistic impact of thick polycarbonate plates by a 7.62 mm armor piercing projectile under the

* Corresponding author.
E-mail address: dorogoy@technion.ac.il (A. Dorogoy).

0734-743X/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijimpeng.2011.05.001

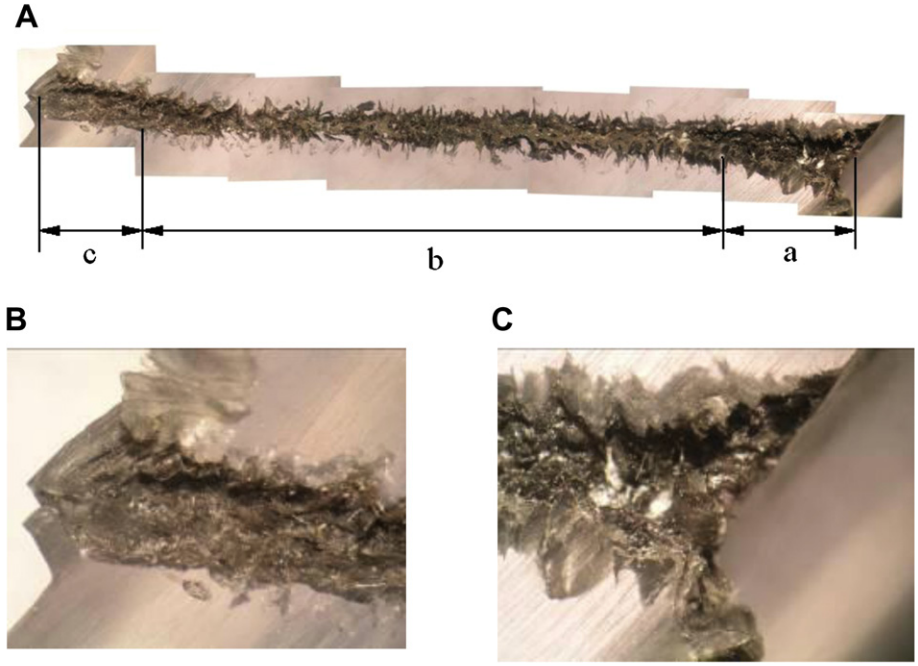

Fig. 1. A section through a typical trajectory within a perforated 50 mm thick polycarbonate plate struck by a 7.62 mm armor piercing projectile. A. The whole section through the trajectory showing: a. Entrance, b. Internal propagation, and c. Exit. B. The exit region. C The entrance region. Note the extensive damage along the trajectory, essentially comprised of microcracks and breakage.

combined effects of tensile (brittle) and ductile failure mechanisms. The investigation is done by performing ballistic experiments aimed at validating the numerical simulations, which can further be used for predictive purposes.

The paper is organized as follows: First the experimental results are presented, followed by the numerical model and its results. The latter are compared to the experimental results and discussed. A study of the maximum depth of penetration in normal impact is then conducted. The main results of this study are then summarized, followed by a concluding section.

2. Experiments

2.1. Experimental setup

The experiments were performed in the Ballistics laboratory at RAFAEL using 7.62 mm armor piercing projectiles. The core of this projectile weighs 4.01 g and the typical muzzle velocity is $\sim$750 m/s. The targets were positioned some 7 m from the gun, at various angles of inclination 0°, 20°, 25°, 30°, 40°, 60° and 80° (relative to the projectile line of flight). The targets were made of 50 mm thick square plates of lateral dimensions 250 $\times$ 80 mm^2. One experiment was conducted using 60° inclination and three layered (but not attached) plates to investigate the depth of penetration. The thickness of the plates in this specific experiment was 40 mm. Three 150 kV flash X-ray tubes were used to follow the penetration of the projectile. Three pictures were recorded. The first was taken just before impact and the following two other pictures covered the time interval of 90–150 μs thereafter. The projectile's trajectory within the targets was recorded and the trajectory length within the plate was measured after the test.

2.2. Experimental results

For a single 50 mm thick plate, bullet ricochet was observed only for a 20° and 25° inclination, while perforation occurred for all the

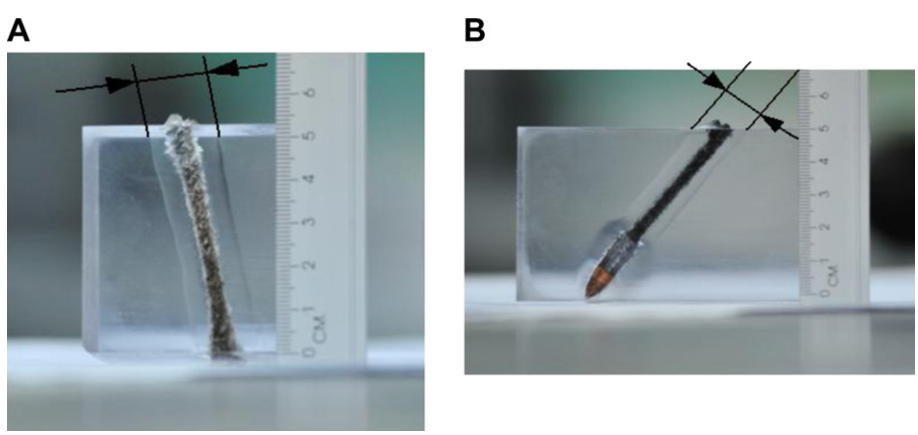

Fig. 2. Trajectory within thick polycarbonate plates. A. Perforation at 80° showing the affected plastic zone around the cavity, marked by arrows. B. A 60° penetration showing the affected plastic zone around the core and the cavity. Note the change of refractive index in the plastic zone, as well as the significant recovery of the cavity along the trajectory, as evidenced from its smaller diameter compared to the core dimension.