

BEHAVIOUR OF TRANSPARENT MATERIAL UNDER HIGH VELOCITY IMPACT

L.H. Abbud¹, A.R.A. Talib¹, F. Mustapha¹, H. Tawfique² and F.A. Najim³

¹Department of Aerospace Engineering, Universiti Putra Malaysia, 43400 Selangor, Malaysia

²Mechanical Engineering Department, University of Al-Nahrain, Baghdad, Iraq

³Ministry of Science and Technology, Al-Jadiriyyah, Baghdad, Iraq

E-mail: abrahim@eng.upm.edu.my

ABSTRACT

The importance of penetration and perforation into targets in both, military and civilian application has made it the subject of many investigations. The current investigation is focused on the ballistic performance of Polymethylmethacrylate (PMMA) under impact by a rigid spherical projectile in the range of 89.3 – 670 m/s. An analytical model for the ballistic limit velocity from the work done for target based on the experimental observations is suggested. The results are discussed in terms of the work done in causing the failure modes coupling this work with the projectiles kinetic energy drop and its effect on the ballistic limit velocity. The effect of target thickness on the velocity is then discussed. The experimental results showed good agreement compared with Ipson and Recht equation.

Keywords: High velocity impact, PMMA performance, Residual velocity, Ballistic limit velocity

1. INTRODUCTION

The subject of this research work deals with materials that have the dual properties of being visually transparent and resistant to penetration by high energy projectiles and fragments. These materials, albeit loosely defined, have received considerable attention in military research and development establishments mainly for protection on the face and head area for military personnel as well as civilians. These transparent materials have been used extensively over the years in automotive, aerospace, defence and buildings industries (Laible, 1980).

Investigation on transparent armored materials under impact on ceramic materials, glass and polycarbonate was reported by Straßburger (2009). Hard front layer of transparent ceramic materials were subjected to projectile of 7.62 mm x 51 AP steel with a total mass of 9.5 g. The impact velocity was kept constant at nominally 850 ± 15 m/s. It was found that the protective strength increased proportional with thickness. The materials efficiency in term of strength was observed in the thickness range from 1 to 2 mm.

Klement et al. (2008) used transparent materials and two types of projectiles; 7.62 mm x 51 AP8 and 7.62

mm x 54R B32 API projectiles. The striking velocity of projectiles in the experiments were set at 930 m/s and 854 m/s respectively against 8 mm thick float glass layers and 7 mm thick sapphire front-face layers (Al_2O_3 single crystal). It was reported that the ballistic results of three layered composite amours sapphire front-face layer have significantly higher ballistic performance. Rittel and Brill (2008) reported the static and dynamic mechanical behavior of confined commercial polymethylmethacrylate (PMMA). PMMA was found to exhibit brittle failure and observed brittle ductile transition which is identical in its principle to that observed in other brittle (ceramic) material system and brittle failure consists of radial cracking and fragmentation.

A new analytical model for predicting the perforation characteristics of unbounded multi-layered composite plates was proposed by Kasano and Abe (1997). Two models were introduced to predict the perforation characteristic of a single layered plate, which are based on the conservation laws of momentum and / or energy. These models are extended to model for n-layered to predict the residual velocity of a projectile after perforation as well as the ballistic limit velocity. Spherical steel projectiles were used to produce impact velocity in the range of 86.5 - 321.9 m/s. It was reported that the residual velocity predicted from the model fairly agreed with the available experimental results for aluminium layered plates.

The work reported here is focused on investigating the ballistic performance of PMMA under impact by a rigid spherical projectile in the range of 89.3 – 670 m/s. An analytical model for the ballistic limit velocity from the work done for target based on the experimental observation is proposed. The results are discussed in term of the work done in causing the failure modes coupling this work with the projectiles kinetic energy drop and its effect on the ballistic limit velocity. The effect of target thickness on the velocity is also discussed.

2. EXPERIMENTAL SET-UP

2.1 Test Specimens Preparation

Test specimens were prepared using panels of transparent material namely polymethylmethacrylate

(PMMA). PMMA is a kind of polymers known for its fair properties and low cost. The material panels were prepared to 100 x 100 mm in size. The materials also being cut for the tensile test according to the standard dimension (ANSI/ASTM D 638-77). Tensile test was carried out on INSTRON 1195 test equipment at the rate of 10 mm/min. The properties obtained for the PMMA were listed in Table 1.

2.2 High Velocity Test

High velocity tests were carried out using the high velocity test rig shown schematically in Figure 1. Basically, the rig consisted of a gun barrel of 7.85 mm nominal bore and 480 mm in length. Two specially designed velocity measurement apparatus were

mounted in front and behind the target holding frame respectively. Each unit consisted of two spaced shorting grids connected to an electronic time counter. The time counter starts as the projectile cuts the wires as it approaches the first grid and is later stopped when the projectile cuts the wires at the next grid. Steel spherical projectile of 85-87 HRB hardness, 7.8 mm in diameter weighing approximately 2.05 g is propelled up to 950 m/s velocity using commercial powder gun charges. Various projectile velocities were obtained by manipulating the weight of powder gun charges. Test targets were clamped between two steel constrained plates with 70 mm center aperture and firmly tightened. The striking velocity and the residual mean velocity were estimated respectively by dividing the distance between two consecutive grids by the counted time.

Table 1 Properties of PMMA material

Material	E (GN/m ²)	Elastic limit σ_y (MN/m ²)	Density ρ (g/cm ³)	Tensile strength (MN/m ²)	Poisson's ν Ratio
Polymethylmethacrylate (PMMA)	3.28	53.8	1.19	48.3	0.28

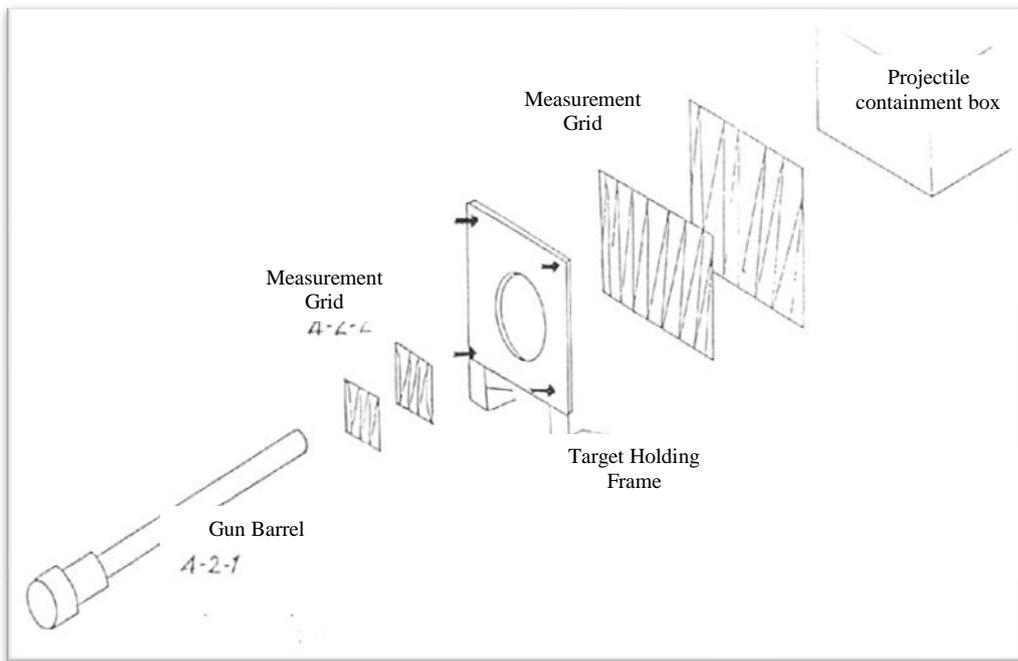


Figure 1 Schematic drawing of the high velocity test rig.

2.3 Polymethylmethacrylate Target model

The analytical model of the penetration and perforation of a spherical rigid projectile against a thin PMMA target plate clamped at its outer periphery will be based on an energy approach where the loss of the kinetic energy of the

projectile $\Delta K.E.$ is equated to the elastic work done in the deformation of the W_E ,

$$\Delta K.E = \frac{1}{2} [m(V_i^2 - V_r^2)] = W_E \quad (1)$$

(m being the mass of the projectile, V_i and V_r are the initial and final projectile velocities respectively).

Elastic work W_E is the elastic energy stored in the target plate during the penetration process. Al-Ghabban (1996) showed that for a clamped circular plate of radius (R), subjected to a central concentrated load (P), the central deflection (W_E) may be written according to Timoshenko (1982);

$$W_E = \frac{P_o^2}{2K} = \frac{3\pi\sigma_y^2}{8E} hR^2(1 - \nu^2) \quad (2)$$

$$\frac{1}{2}mV_b^2 = \frac{3\pi\sigma_y^2}{8E} hR^2(1 - \nu^2) \quad (3)$$

$$V_b^2 = \frac{2}{m} \left\{ \frac{3\pi\sigma_y^2}{8E} hR^2(1 - \nu^2) \right\} \quad (4)$$

Now, solving for the ballistic limit velocity V_b

$$V_b = \frac{2}{m} \left\{ \frac{3\pi\sigma_y^2}{8E} hR^2(1 - \nu^2) \right\}^{1/2} \quad (5)$$

Equation (5) gives the ballistic limit velocity of a target as a function of its physical and geometric properties.

Where, P_o is plastic collapse load of the structure, σ_y is yield stress, E is young's modulus, H is plate thickness, R is plate radius and ν is poisson's ratio .

3. RESULTS AND DISCUSSION

3.1 Targets Mode of PMMA

Figure 2 (a), (b) and (c) shows photos taken on several targets of different thicknesses of Polymethylmethacrylate material. The failure modes shown upon being impacted by a spherical projectile driven at 100 m/s. Upon impact, the area of impact experiences high stresses both in the radial and hoop directions. However, the star crack pattern proves that the stresses in the hoop direction becomes much higher than the maximum tensile stress permitted in the material causing eventually the fracture of the material in that vicinity in a star shape. As the projectile moves on driven by the driving momentum through the target material, effected zone shows radial shaped cracks forming several concentric cracks around the projectile, target contact zone on further progress of the projectile, the cracked zone were pushed forward in front of the projectile tip in a conical plug form. Finally the projectile emerges from the rear target side pushing a plug of two to three times the

diameter of the lumping projectile as shown in Figure 3.

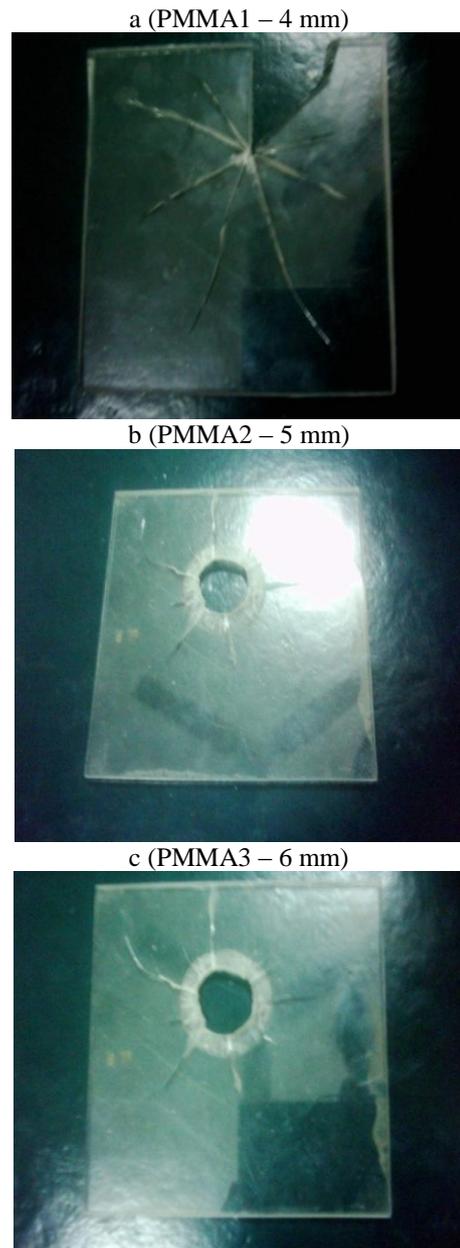


Figure 2 Photos taken on PMMA after impact by a spherical projectile at 100 m/s.

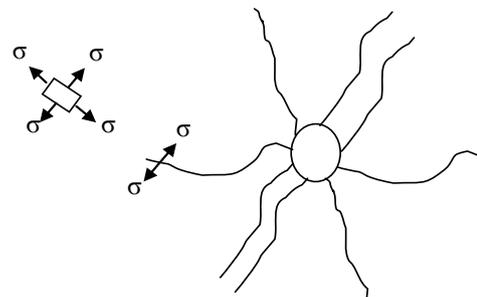


Figure 3 Schematic behavior of PMMA after impact

The residual velocity V_r is based on a power function of the initial velocity and the ballistic limit as follows:

$$V_r = \sqrt{V_i^2 - V_b^2} \quad (6)$$

Where, V_r is the final velocity, V_i is the initial velocity and V_b is the ballistic limit.

Figures 4, 5 and 6 shows the final velocity for PMMA target versus the initial velocity for single layer for target thickness 4, 5 and 6 mm respectively. The final velocities were compared

against empirical formula by Ipson and Recht (1963). It was observed that results were in good agreement within 12-17% of error.

The theoretical ballistic limit velocity V_b in equation (5) as shown in Table 2 gives good correlation with the experimental results as shown in Figure 7.

Figure 8 shows the effect of target thickness on the elastic work done for PMMA. It can be observed that the elastic work done is purported to the thickness as presented in equation (2).

Table 2 Comparison between the theoretical and experimental results for velocity ballistic limit

Material	Thickness (mm)	V_b Theoretically (m/s)	V_b Experimentally (m/s)	Error %
PMMA ₁	4.00	78.15	89.30	12.48
PMMA ₂	5.00	87.37	100.32	12.90
PMMA ₃	6.00	95.71	115.60	17.20

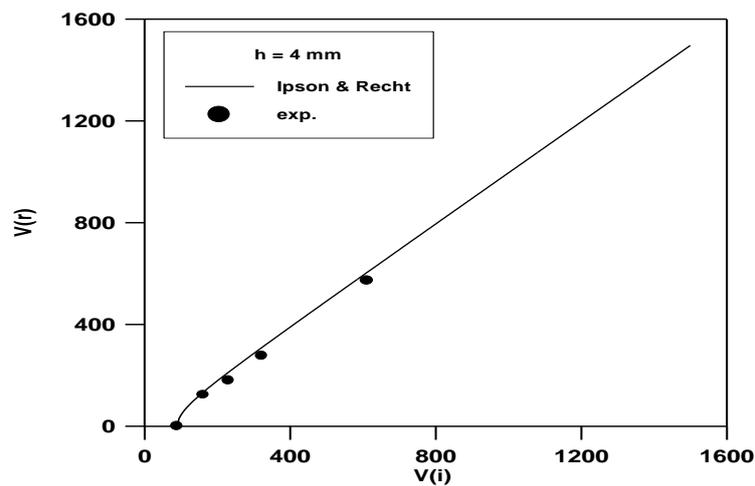


Figure 4 Final velocity V_r versus initial velocity V_i for PMMA₁ – 4 mm by sphere projectile

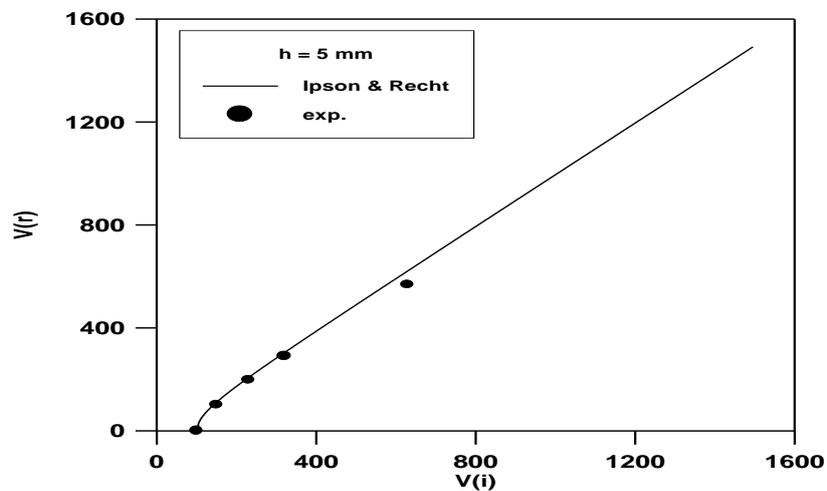


Figure 5 Final velocity V_r versus initial velocity V_i for PMMA₂ – 5 mm

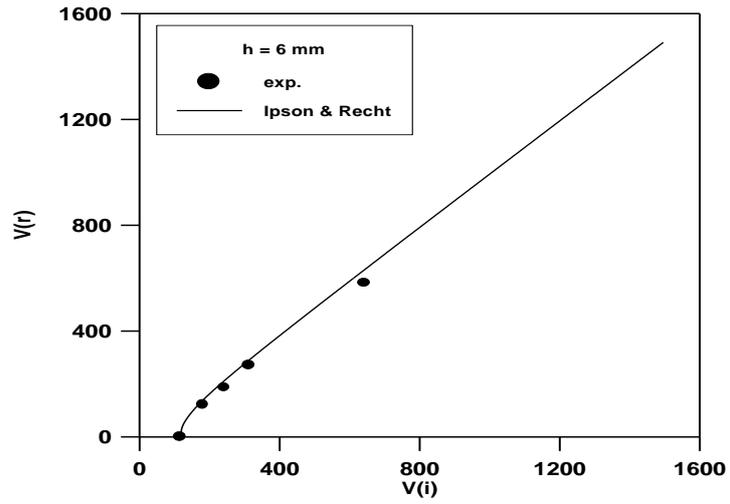


Figure 6 Residual velocity V_r versus initial velocity V_i for PMMA₃ – 6 mm

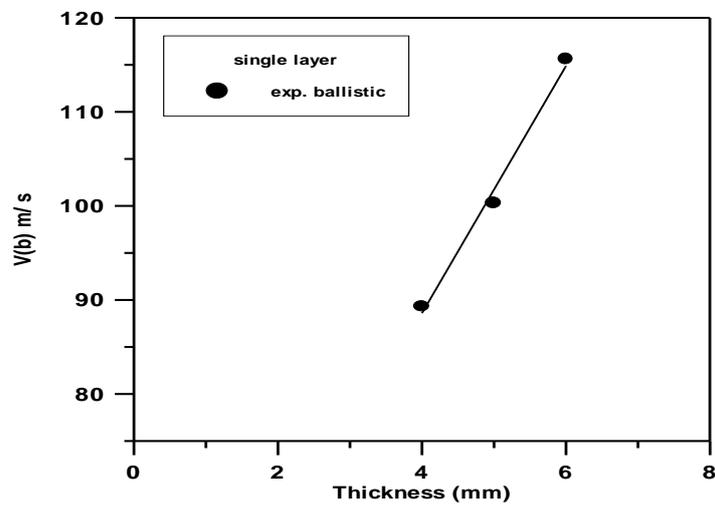


Figure 7 Experimental ballistic limit velocities for PMMA₁, PMMA₂ and PMMA₃₁

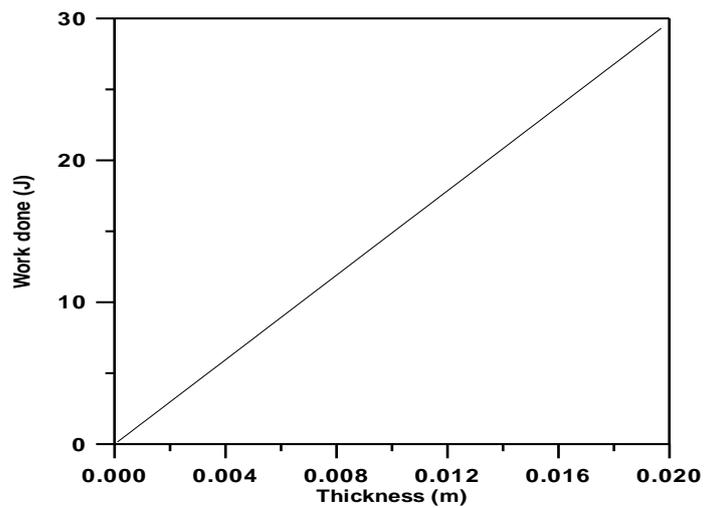


Figure 8 The effect of target thickness on the elastic work done for PMMA target

4. CONCLUSION

An analytical model for the ballistic limit velocity from the work done for target based on the experimental observations was presented. The experimental results showed good agreement compared with Ipson and Recht equation. It was observed that increased thickness of PMMA resulted a higher absorbing energy and more resistant to ballistic impact.

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REFERENCES

- D. Rittel, and A. Brill, 2008, Dynamic flow and failure of confined polymethylmethacrylate, *Journal of the Mechanics and Physics of Solids*, Volume 56, pp. 1401–1416.
- E. Straßburger, 2009, Ballistic testing of transparent armour ceramics, *Journal of the European Ceramic Society*, Volume 29, pp. 267 –273.
- I.A.H. Al-Ghabban, 1996, Analytical model for the behavior of multi-layered targets under projectile impact, Ph.D. Thesis, University of Technology, Baghdad.
- Kasano H. and Abe K., 1997, perforation characteristics prediction of multi-layered composite plates subjected to high velocity impact, In: *Proceedings of ICCM-11*, Gold Coast, Australia, July.
- Klement, R., Rolc, S., Mikulikova, R., and Krestan, J., 2008, Transparent armour materials, *Journal of the European Ceramic Society*, Volume 28, No. 5, pp. 1091 - 1095.
- Laible R.C., 1980, *Ballistic materials and penetration mechanics*, Elsevier Scientific Publishing Co., Amsterdam.UK.
- Recht R.F. and Ipson, T.W., 1963, Ballistic perforation dynamics, *Journal of Applied Mechanics*, Volume 30, pp. 384 – 390.
- Timoshenko, S. and Goodier, J., 1982, *Theory of Elasticity*, 3rd Ed. McGraw-Hill, Tokyo.