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Oblique Impact of Projectile on Thin Aluminium Plates

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ABSTRACT

Experiments were performed, wherein cylindrical projectiles made of hardened steel were impacted on commercially available aluminium plates at different angles. Projectiles were of 12.8 mm diameter and plates were of 0.81 mm, 1.52 mm and 1.91 mm thicknesses. Based on the experimental results, an analytical model has been developed to predict the residual velocity of the projectile and the ballistic limit of the plate.

Keywords: Oblique impact, impact velocity, projectiles, ballistic limit, residual velocity, plates, aluminium plates, analytical model, projectile velocity

NOMENCLATURE

a	A constant that depends upon the profile of the plate
D_s	Diameter of the striker (projectile)
D_p	Diameter of plug
E_{ao}	Total energy absorbed by the plate
E_{dn}	Energy absorbed in normal dishing
E_{do}	Energy absorbed in oblique dishing
E_{sn}	Energy absorbed in normal shearing
E_{so}	Energy absorbed in oblique shearing
h_o	Target plate thickness
L	Length of the projectile
r_p	Radius of the projectile
v_{50}	Ballistic velocity
v_i	Impact velocity
v_r	Residual velocity
β	Target obliquity from normal
δ	Change in penetration path
ρ_t, ρ_s	Density of target and striker.

1. INTRODUCTION

Phenomena of normal and oblique impacts on thin plates is of interest in many engineering applications like crashworthiness of vehicles, design of lightweight body armour, and some production processes. Normal impact phenomenon has been studied extensively

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over the years[1-4], however, the oblique impact has not been studied much.

Normal and oblique impacts were studied by Awerbuch and Bodner[5] by performing experiments on aluminium plates at 0° to 45° obliquity by projectiles of 0.22 in. caliber at constant impact velocity of 385 m/s. After modifying their model[6], they found that the angle of impact had insignificant effect on the velocity drop over a range of angles of impact. The influence of the impact angle becomes more near the ballistic limit. Piekutowski[7], *et al.* conducted experiments at normal and oblique impacts on 6061-T651 aluminum plates, by ogive-nose steel rods. They have developed a model, which predicts the ballistic limit and residual velocities for the limited data (at 30° obliquity).

Thomas and Kevin[8] carried out experimental and analytical studies for determining the position and orientation of ogive-nosed steel projectile at 15°, 30° and 45° obliquities in the ordnance velocity range. They also considered the projectile deformation.

Goldsmith and Finnegan[9] studied the normal and oblique impacts of cylindro-conical and cylindrical projectiles on metallic plates. Hard steel projectiles of 12.7 mm diameter with either 60° conical or blunt tips and blunt soft aluminium cylinder of the same diameter, were fired at 2024-0 aluminium targets with thickness ranging from 1.78 mm to 24.4 mm and both mild steel and medium carbon steel plates with thickness up to 19.05 mm. Initial target obliquity varied from normal to 50°. The velocity drop and change in projectile orientation were measured along with the target damage consisting of dishing, petals, plug, and bends.

Gupta and Madhu[10] performed a series of experiments, wherein spinning armour piercing projectiles of core diameter 6.2 mm were fired on mild steel plates of thickness varying from 10 mm to 25 mm. The projectile velocity in all the tests was about 820 m/s in both the normal and the oblique impacts. The angle of obliquity was increased from normal impact until ricochet occurred. In another study, Gupte and Madhu[11] carried out similar experiments on single and layered targets. The plate thickness was varied from 4.7 mm to 40.0 mm. They determined the thickness of the plates for which the incident velocity was the ballistic limit.

These authors present a study of oblique impact of cylindrical hardened steel projectiles on aluminium plates of different thicknesses at varying impact velocities in subordnance velocity range. Five angles of obliquity and three plate thicknesses were used. The impact and residual velocities and profile of the perforated specimen were measured. An analytical model, based on the experimental results, has been developed to predict the residual velocity of the projectile and ballistic limit of the target plate at different angles of obliquity.

2. EXPERIMENTAL SETUP & PROCEDURE

Hardened cylindrical steel projectiles of 12.8 mm diameter and 25.6 mm length were impacted, through a pneumatic gun, at velocities ranging from ballistic limit of the plate to about 106 m/s. The pneumatic gun, designed and fabricated in house, is capable of firing projectiles of diameters up to 15 mm at varying impact velocities, up to 150 m/s. Target plates of different sizes can be mounted in front of the gun barrel at any impact angle between 0° to 90°. Five different incident angles, viz., 0°, 15°, 30°, 45°, and 60°, and three plate thicknesses, viz., 0.81 mm, 1.52 mm, and 1.91 mm have been selected for this study. Plates of 255 mm diameter were cut from commercially available pure aluminium sheets. The average yield strength of aluminium plates is 110 MPa. The mass of the projectile and its hardness were 25.08 g and 58 Rc, respectively.

The velocity of the projectile before impact was measured with the help of two sets of photoemitter and diodes placed 25 mm apart at the exit of the barrel. The residual velocity of the projectile was measured with the help of two sets of thin aluminium foil screens, 50 mm apart, placed behind the target at a fixed distance. Impact and residual velocities were measured in each run with the help of a 4-channel digital storage oscilloscope[12] (Tektronics TDS-224).

The experimental ballistic limits of the plates of different thicknesses at different angles of obliquity

Table 1. Ballistic limit of aluminium plates of different thicknesses at different angles of obliquity

Angle of obliquity (deg)	Ballistic limit (m/s) of the plates		
	Plate thickness (mm)		
	0.81	1.52	1.91
0	28.8	45.3	51.0
15	24.4	40.3	50.8
30	23.4	39.3	55.7
45	37.3	45.3	57.0
60	48.8	52.9	79.3

are given in Table 1. The profile of the deformed specimens was measured from the distal sides of the plates with the help of a dial gauge setup and is used for the determination of energy absorbed in the dishing of the plate. Experimental results thus obtained are plotted, wherein the effects of plate thickness and angle of obliquity on residual velocities and energy absorbed are discussed.

2.1 Effect of Plate Thickness

The measured values of residual velocity at different impact angles are plotted against impact velocities in Figs 1 and 2, for aluminium plates of all thicknesses employed. It is seen that residual velocity increases with increase in impact velocity for each thickness. This increase is more rapid initially (near the ballistic limit) and later, the curve of residual velocity versus impact velocity tends to become parallel to the 45° line as shown in the Figures.

The effect of impact energy on the energy absorbed by the plates during perforation is shown in Figs 3 and 4. The absorbed energy is almost constant at different impact energy levels of the projectile for a particular plate thickness, in the velocity range employed. The absorbed energy increases with an increase in the plate thickness.

2.2 Effect of Obliquity

The measured values of the residual velocities are plotted against the impact velocities for a given plate thickness at different angles of obliquity are shown in Fig. 5. The residual velocity, in general, decreases with increase in the angle of obliquity. This effect is much significant at lower impact velocities than at higher impact velocities.

The effect of impact energy on the energy absorbed by the plates at different angles of obliquity during perforation shows a trend similar to the trend shown in Figs 3 and 4. The absorbed energy

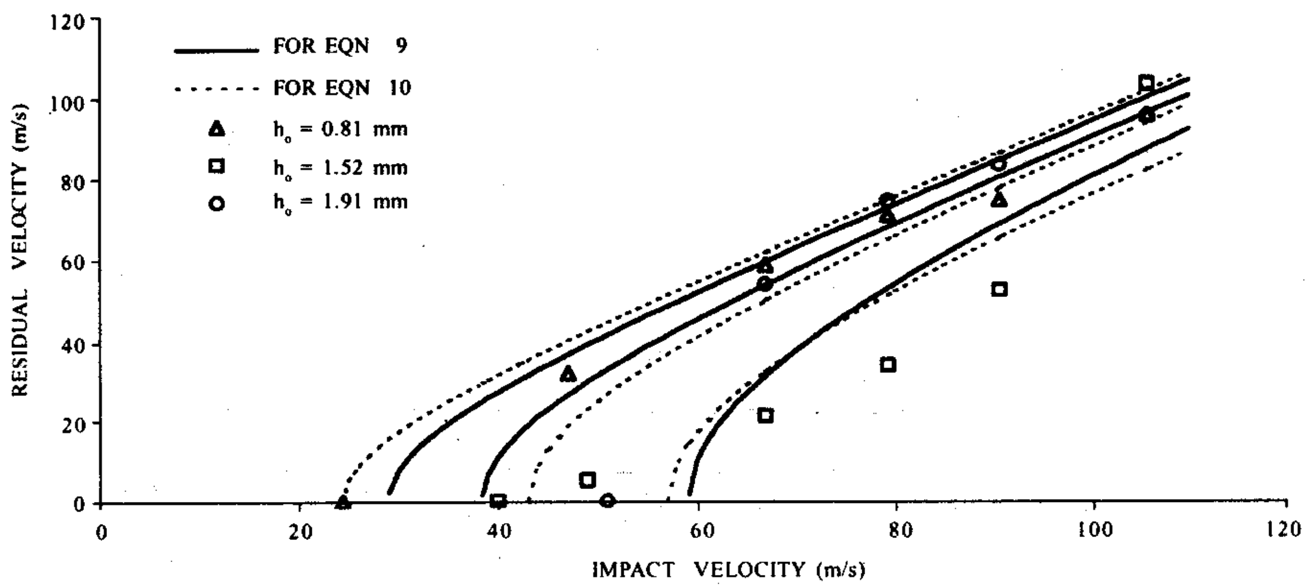

Figure 1. Comparison of experimental residual velocity for 15° obliquity of different thicknesses of aluminium plates with the results obtained from Eqns (9) and (10).

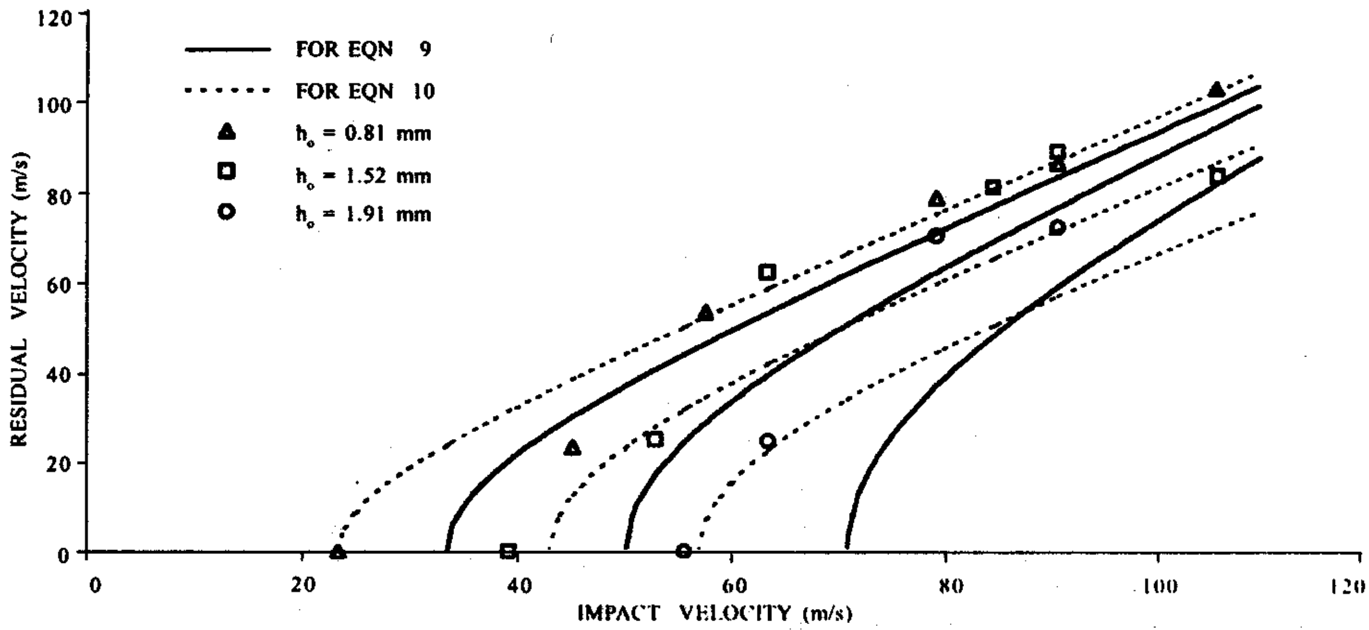

Figure 2. Comparison of experimental residual velocity for 30° obliquity of different thicknesses of aluminium plates with the results obtained from Eqns (9) and (10).

is almost constant at different impact energy levels of the projectile for a particular plate thickness, in the velocity range employed. The absorbed energy increases with an increase in the angle of obliquity.

The mode of deformation of an aluminium plate is affected by the angle of obliquity. A circular plug is formed in a normal impact, whereas an elliptical plug is formed in an oblique impact. Dishing of the plate is almost uniform throughout the circumference of the perforated plate in normal impact, whereas dishing is more in upper half than in the lower half of the plate.

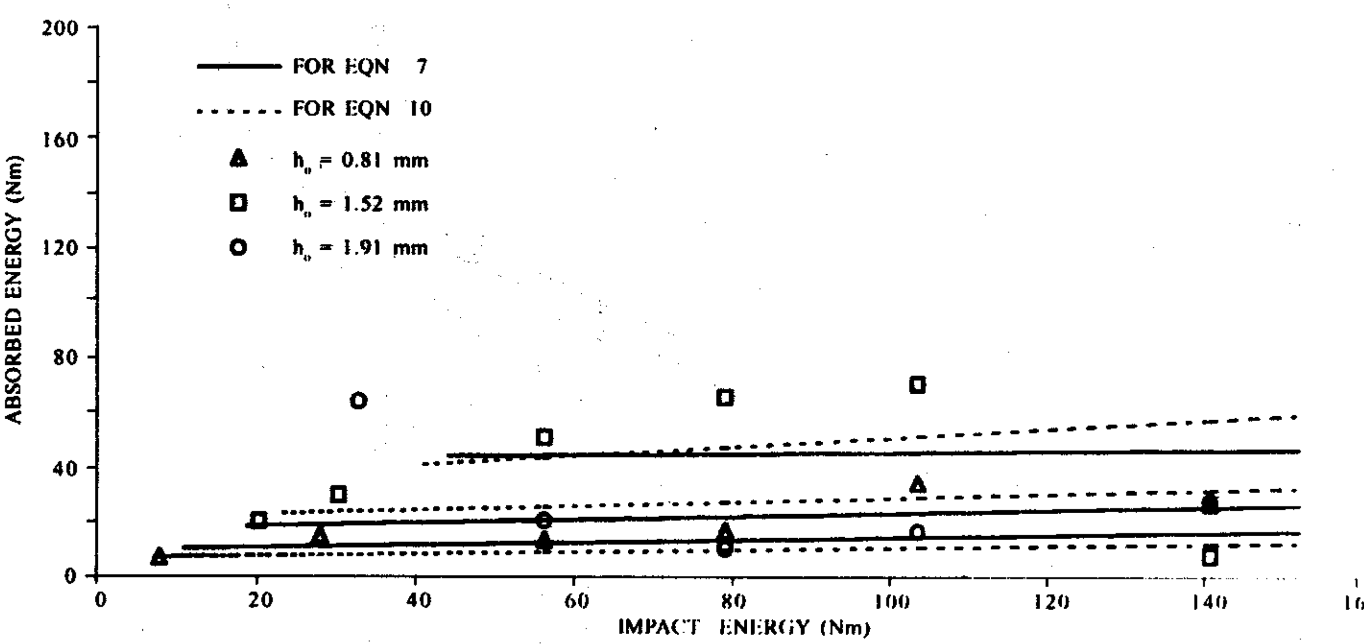

Figure 3. Comparison of experimental residual velocity for 15° obliquity of different thicknesses of aluminium plates with the results obtained from Eqns (7) and (10).

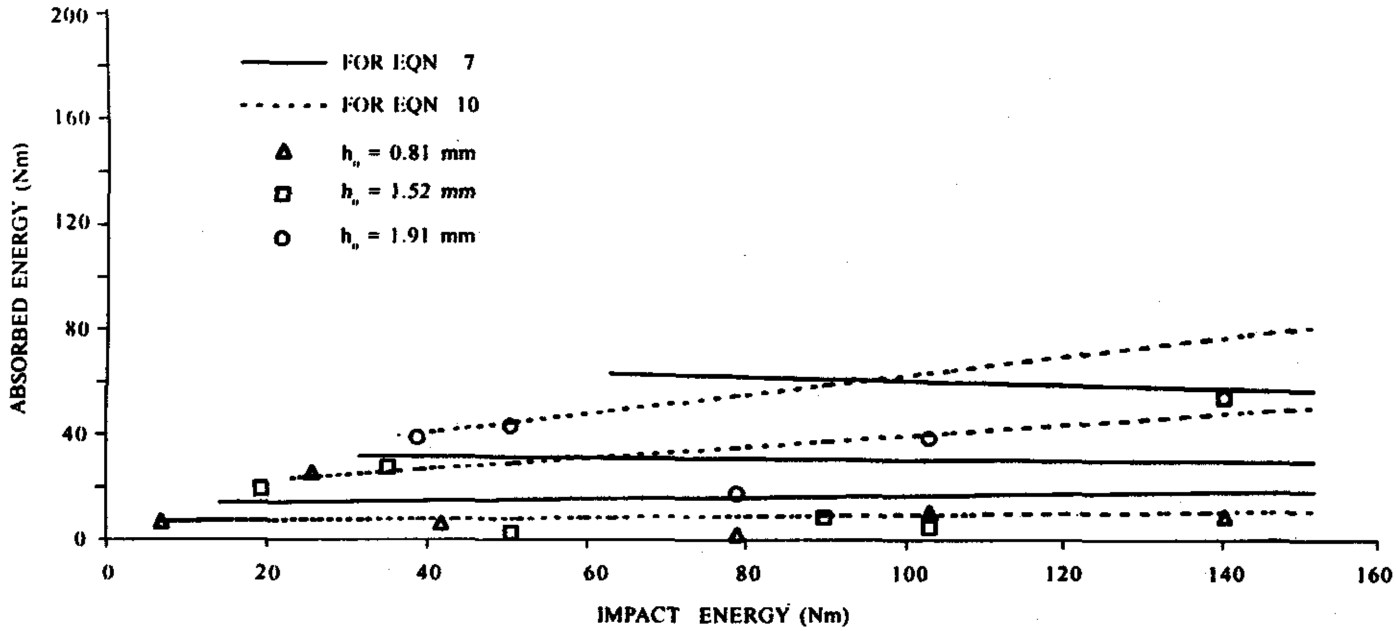

Figure 4. Comparison of experimental residual velocity for 30° obliquity of different thicknesses of aluminium plate with the results obtained from Eqns (7) and (10).

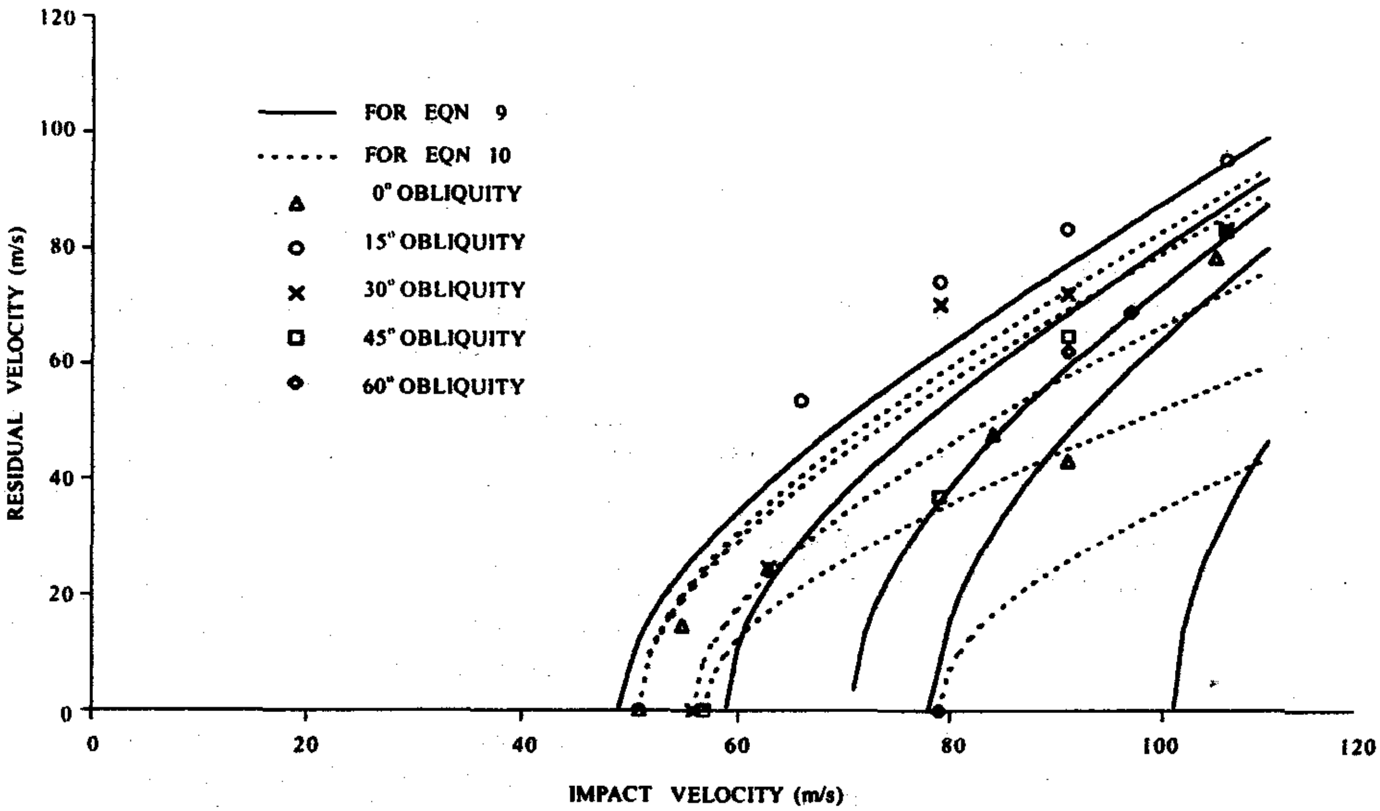

Figure 5. Comparison of experimental residual velocity for aluminium plate of 1.52 mm thickness at different angles of obliquity with the results obtained from Eqns (9) and (10).

3. ANALYSIS

The experiment shows that the primary modes of failures, in thin plates of ductile materials are dishing along with shearing of a plug, when impacted by a cylindrical projectile. This is a common phenomenon in normal as well as oblique impacts in the employed velocity range. Thus, the energy of the projectile absorbed during perforation is of two types: (i) energy absorbed in shearing of a plug and (ii) energy absorbed in the plate bending.

The energy absorbed in normal shearing[13] of a plug is taken as

$$E_{sn} = (2\pi r_p h_o)\, 0.6 h_o \sigma_s \qquad (1)$$

where E_{sn} is the energy absorbed in normal shearing, r_p is the projectile diameter, h_o is the plate thickness, and σ_s is the shearing strength of the plate material.

In an oblique impact, the shear area A_s and effective plate thickness, h_{eff} is taken as

$$A_s = \pi r_p (1+\cos\beta) \frac{h_o}{(\cos\beta)^2} \qquad (2)$$

$$h_{eff} = \frac{h_o}{\cos\beta} \qquad (3)$$

where β is the angle of obliquity from normal. So, the energy absorbed in shearing of a plug in an oblique impact is

$$E_{so} = \frac{0.6\pi r_p (1+\cos\beta) h_o^2 \sigma_s}{(\cos\beta)^3} \qquad (4)$$

The energy absorbed in radial stretching (plate bending) in normal impact[14] is given by

$$E_{dn} = \frac{\pi h_o w_c^2 \sigma_y e^{-2ar_p}(1+2ar_p)}{4(1-\nu+\nu^2)^{1/2}} \qquad (5)$$

where w_c is the central deflection of the plate, a is a constant measured from profile of the perforated plate and ν is the Poisson's ratio

The energy absorbed in dishing of the plate during oblique impact is evaluated by replacing the thickness of the plate, h_o with the effective thickness, h_{eff}

$$E_{do} = \frac{\pi(h_o/\cos\beta) w_c^2 \sigma_y e^{-2ar_p}(1+2ar_p)}{4(1-\nu+\nu^2)^{1/2}} \qquad (6)$$

Now, the total energy absorbed during deformation of the plate is

$$E_{ao} = \frac{0.6\pi r_p (1+\cos\beta) h_o^2 \sigma_s}{(\cos\beta)^3} + \frac{\pi(h_o/\cos\beta) w_c^2 \sigma_y e^{-2ar_p}(1+2ar_p)}{4(1-\nu+\nu^2)^{1/2}} \qquad (7)$$

The equation of energy balance, then may be written as

$$\frac{1}{2} m v_i^2 = \frac{1}{2} m v_r^2 + E_{ao} \qquad (8)$$

where v_r is the residual velocity of the projectile which may be written as

$$v_r = \sqrt{v_i^2 - \frac{2E_{ao}}{m}} \qquad (9)$$

Residual velocities of the projectiles for different target plate thickness at different angles of obliquity were computed with the above equation. This shows good agreement with the experimental results. Putting the residual velocity equal to zero in Eqn (10), the impact velocity of the projectile will be equal to the ballistic limit of the plate. The absorbed energy calculated from Eqn (8) is plotted against impact energy for different plate thickness at different angles of obliquity, which matches well with the experimental results.

4. COMPARISON OF EXPERIMENTAL DATA WITH EXISTING MODEL

Experimental results of the present study are also compared with an existing model[15] and are shown by dotted lines in Figs 1-5. The residual velocity is given as

$$v_r = \left(\left[v_i^2 - v_{50}^2 \right]^{1/2} \cos\delta \right) \Bigg/ \left[1 + \left\{ \frac{\rho_t}{\rho_s} \right\} \left(\frac{D_p}{D_s} \right)^2 \left(\frac{h}{L\cos\beta} \right) \right] \tag{10}$$

5. CONCLUSIONS

A model has been developed, on the basis of reasonably sufficient number of experiments, to compute residual velocity of the projectile in oblique impact of the cylindrical projectile, on aluminum plate. These experiments were carried out at different angles of obliquity, between 0° and 60°. The model is capable of computing residual velocity and related parameters by just performing a single experiment at a particular obliquity. The model does not require the ballistic limit of the plate for computing the residual velocity, which is commonly required in many existing models[15]. The computed values show good correlation between experimental and computed values in the velocity range employed.

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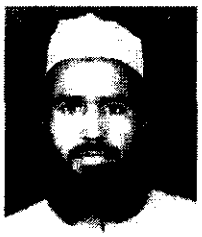

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