AN EXPERIMENTAL STUDY OF NORMAL AND OBLIQUE IMPACT OF HARD-CORE PROJECTILE ON SINGLE AND LAYERED PLATES

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Summary—An experimental study of the normal and oblique impact of armour-piercing projectiles on single and layered plates of mild steel, RHA steel and aluminium is presented. The projectiles were fired at an impact velocity of \(\approx 800-880\) m s\(^{-1}\). The plate thickness varied in the range 4.7–40 mm and the ratio of the plate thickness to the diameter of the projectile varied in the range 0.75–4.5 for single plates and up to 13 for layered plates. Observations on target damage and measurements of incident and residual velocities and the angles in normal and oblique impact are presented. Determination of plate thickness \(t\), for which the incident velocity is the ballistic limit, is considered and influences of various parameters, like plate material and its thickness, on \(t\) and the residual velocity are discussed. Relations are developed to determine the residual velocity for a plate of thickness less than \(t\), and to relate \(t\) with the hardness of the material. Results for the residual velocity obtained from these relations are compared with those from the experiments.

Keywords: normal impact, oblique impact, plates, perforation, ricochet.

1. INTRODUCTION

The phenomenon of ordnance velocity impact of a projectile on single and layered plates is of interest in many applications. Backman and Goldsmith [1], Zukas [2] and Corbett et al. [3] have reviewed studies which deal with the experiments and analytical formulation for determining ballistic limit of a single plate and the residual velocity of projectiles for incident velocities greater than the ballistic limit.

In normal impact studies that have appeared in literature [4–17], the plate thicknesses have generally been small, less than 10 mm. Thompson [12] proposed a theory based on energy approach for the penetration of conical and ogival shaped projectiles. The momentum approach has been used in Refs [13,14]. A mathematical model to describe the perforation process — which was divided into three interconnected stages, i.e. target compression, shear and plug formation — was developed by Awerbach and Bodner [15]. Ravid and Bodner [16] later formulated a model for the dynamic perforation of visco-plastic plates impacted by rigid, flat-ended projectiles in five interconnected but distinct stages: dynamic plastic penetration, bulge formation, bulge advancement, plug formation and projectile exit. The one-dimensional problem of expansion of spherical or cylindrical cavities has been solved in [17], by assuming that the shear stresses at the projectile surfaces are negligible relative to the normal stresses.

As given by Lambert and Jonas [18], many of the previously derived expressions for the residual velocity may be written in the form

\[
V_r = \begin{cases} 
0, & V_i < V_{BL} \\
\alpha(V_i^p - V_{BL}^p)^{1/p}, & V_i > V_{BL}
\end{cases},
\]

where \(V_i\), \(V_r\) and \(V_{BL}\) are the striking, residual and limit velocities of the projectile (in m s\(^{-1}\)), and

\[
\alpha = \frac{M}{M + M^* / 3}, \quad p = 2 + \frac{z}{3}, \quad z = \frac{t}{d} \cot \theta
\]

where \(M\) is the penetrator mass (in g), \(M^*\) is the mass of the target material projected in front of the penetrator prior to impact, \(t\) is the target thickness (in cm), \(d\) is the projectile diameter (in cm) and \(\theta\) is the angle of incidence which is zero for normal impact. Other individual models differ mainly in the formulation of \(\alpha\) and \(V_{BL}\).

Experiments on multi-layered targets available in literature are rather few, and the benefits of using multi-layered plates as against monolithic plates of equal thickness are not clear as yet. Normal impact of hard-steel blunt and conically nosed projectiles on multi-layered plates of soft aluminium, both
adjacent and spaced, and on adjacent disks of thin aluminium and polycarbonate, including their sandwich arrangements, were studied experimentally [19] in the vicinity of their ballistic limit. It was found that the ballistic resistance of the monolithic target was greater than that of the layered target of corresponding total thickness. Marom and Bodner [20] made an analytical and experimental study on the ballistic resistance of thin, flat beams of pure aluminium and 6061-T6 aluminium alloy, both in contact and spaced, for impact of 0.22 in calibre projectiles at 375 m s⁻¹ and found that the multi-layered beams in contact showed greater resistance to penetration than the equivalent monolithic beam which, in turn, were more efficient than the separated flat beams of equal weight. Corran [6] investigated the performance of multi-layered steel plates under projectile impact and found that layers placed in contact were superior to monolithic single plates if the adoption of multiple layers changed the response of the plates from being one dominated by plate bending and shearing to one dominated by membrane stretching. Nixdorff [21] applied the empirical theory given in Ref. [22], and an approximate analytical approach given in Ref. [15] which was developed for estimating the parameters of penetration of monolithic targets to multi-layered targets. Hetherington and Rajagopalan [23] investigated the response of target plates consisting of a ceramic front layer and an FRP on the rear. This combination seemed to be very effective in withstanding projectile impact in terms of energy absorbed per unit area density.

There are relatively few investigations that have been carried out on oblique impact of rigid projectiles on targets [24–29]. Goldsmith and Finnegan [27] gave plots of non-dimensional velocity drop against initial obliquity and showed that at higher impact velocities there is little change in the angle of flight of projectile during the penetration process. At lower velocities, the final angles of exit of projectiles were found to be less than the initial angle of impact. Awerbuch and Bodner [15] developed a mathematical model to describe the perforation process, which is shown in Ref. [28] to be applicable for oblique impact when the presented area and thickness of projectile path through the plate were considered.

In this paper, we considered normal and oblique impacts of a jacketed hard-core ogival shaped projectile, at velocities of the range 800–880 m s⁻¹, on single and layered plates of mild steel, RHA steel and aluminium. The single-plate thicknesses were 4.7–40 mm for different materials. Mild steel and aluminium plates were obtained in different lots and their material properties varied with each lot. Experiments reported in this paper were performed to:

1. determine the plate thickness \( r^* \), for which the given incident velocity is the ballistic limit;
2. for this incident velocity, determine the residual velocity for a single plate of thickness less than \( r^* \);
3. compare the response of single plates with those of layered plates in normal impact, and with single plates in oblique impact;
4. determine the incident angle for a given plate thickness \( r \), for which the incident velocity is the ballistic limit, and the angle for ricochet; and
5. to study the variation of \( r^* \) with the variation of material property.

The aim is to provide data and develop simple relations to be able to determine: (a) the ballistic limit thickness \( r^* \) of a plate of given material and for the given incident velocity of the present hard-core projectiles; and (b) the residual velocity for a plate of a given material and of thickness less than \( r^* \), in normal or oblique impact, and for layered plates in normal impact.

The results reveal that the response of multi-layered targets, when the individual plate thickness is greater than \( \sim r^*/4 \), is about same as that of single plates of equal thicknesses. However, for thinner plates, the residual velocity for a layered target is higher than the residual velocity for a corresponding single plate. Layered plates with spacing give still higher residual velocities. The angles of exit in oblique impact are lesser or greater than the incidence angles depending on the hardness and thickness of the plate material.

2. EXPERIMENTAL

Experiments were performed in a small arms range wherein hard-core armour-piercing projectiles were fired at nearly same velocity on different plates of mild steel, RHA steel and aluminium, using a standard rifle. All the plates were square shaped of \( \sim 200 \text{ mm} \) a side. The testing arrangement is shown in Fig. 1. Mild steel (MS) and aluminium plates (AL) were taken from three different lots, being denoted as MS1, MS2, MS3 and AL1, AL2, and AL3 (see Table 1). The gun was mounted on a rigid mount. The projectile core was 6.2 mm in diameter, 27.6 mm long and weighed 5.2 g. It was ogival in shape and had
a copper sheath, which made up the total diameter of the shot to 7.8 mm. The projectile was made of hard-steel alloy; its hardness at the tip was \( \sim 900 \) VPN. During the course of experiments, the projectiles were drawn from three different lots and, when fired, their velocities before impact were \( \sim 820 \text{ m s}^{-1} \), 835 m s\(^{-1}\) and 865 m s\(^{-1}\) with a variation of less than 1.8% within a lot. The small arms range consisted of a firing chamber, a long tunnel and an observation chamber. The target-holding fixture was located in the tunnel at a distance of 10 m from the gun and could be rotated to hold a plate at any desired angle for oblique impact. All plates were square in shape and were held by their four corners onto the fixture with C-clamps. The stand was then adjusted for the desired angle of impact \( \theta \), which was varied in the range 0–60° in the present experiments. The impact and residual velocities of the projectile were measured in each test with the help of four aluminium velocity foil screens. The first two screens were placed at 6 and 8 m distance from the muzzle of the gun and the other two were placed 0.2 and 0.4 m behind the target. In these experiments, the projectiles were recovered after perforation of the target and no significant deformation to the projectile was observed.

Results of the incident and residual velocities and angles are presented as an average of three tests each. Typical perforated plates are shown in photographs or sketches. The diameters of the holes and their variation along the thickness of the plate are seen to be highly dependent on the plate thickness and its material. This is because the projectile has a copper jacket, which itself has momentum. For thin plates and those with low hardness the jackets may perforate, although it may be stripped from the core in the process. With increase in thickness or/and hardness, the jacket may be jammed and its debris may squeeze out from the exit along with the projectile and thus making the diameter there higher. For high thickness and hardness, the jacket may be stripped close to the entry point and further motion of the projectile (without jacket) would cause much less deformation away from the entry point.

3. NORMAL IMPACT ON SINGLE PLATES

In the present experiments, single plates employed were those of (a) mild steel of thicknesses 4.7 mm (MS1); 6.0 mm (MS2); and 10, 12, 16, 20 and 25 mm (MS3); (b) RHA steel of thicknesses 8, 12, 16 and 20 mm; and (c) aluminium plates of thicknesses 6.0 mm (AL1); 20 mm (AL2); and 10, 20, 30, 33 and 40 mm (AL3). Symbols used for each lot of material are given in brackets. The hardness of all the plates in a lot was same. These plates were subjected to normal impact of the armour-piercing projectiles at a velocity of \( \sim 820, \ 835 \text{ or 865 m s}^{-1} \).
3.1. Mild-steel plates

Mild-steel plates, MS1 and MS2, employed in the present experiments were of 4.7 and 6.0 mm thickness and had Vickers hardnesses of 110–115 and 150-155 VPN, respectively. Thicknesses of the MS3 plates were 10, 12, 16, 20 and 25 mm and their hardnesses were of the range 140–145 VPN. The impact velocity for MS1 and MS3 plates was ~820 m s⁻¹, whereas for MS2 plates it was 865 m s⁻¹. Post-impact observations for MS1 and MS2 showed small petals on the impacted side of the plates. The crater diameters in the front and the rear were 7.5 and 9.1 mm for MS1 plates (shown later in Fig. 7), and 11.6 and 12 mm for MS2 plates.

For MS3 plates, the diameters of the craters in all the plates were larger at the entry point than at the exit point. The plates showed the formation of petals on their front side and a bulge on the rear. The petal height for a plate of lower thickness was small at the front than at the back of the plate. With increase in thickness, the petal height in the front increased; and for the plates of 25 mm thickness, their height at the front and the back were almost equal. Fig. 2 ((a) and (b)) shows typical front and distal damages, respectively, in a 20 mm thick plate, under normal impact. Fig. 3 shows the variation in the front- and rear-crate diameters with plate thickness. This shows that the front diameter first decreases and then increases with increase in thickness; its minimum value was for a plate of thickness 12 mm. The rear diameter increases up to a thickness of 12 mm and then begins to decrease. Thus, for a thick plate, the jacket is stripped earlier and the debris causes extrusion near the entry point. At the exit, it is only the projectile core which comes out and, therefore, the diameter there is nearly equal to the projectile-core diameter.

The impact and residual velocities recorded in these tests are given in Table 2 for all mild steel plates, and the residual velocities are plotted against plate thickness in Fig. 4 for MS3 plates only of all thicknesses.

![Typical front and rear crater damage in normal impact on (i) 20 mm thick mild-steel (MS3) plate: (a) front and (b) rear; and (ii) 30 mm thick aluminium (AL3) plate: (c) front and (d) rear.](image-url)
3.2. Rolled homogeneous armour steel plates

RHA steel plates employed in these experiments were of thicknesses 8, 12, 16 and 20 mm. These plates had a hardness of 290 VPN. For the impact velocity of \( \sim 820 \text{ m s}^{-1} \), the 8 and 12 mm thick plates were perforated. In a 16 mm thick plate, the projectile protruded from the rear side of the plate by \( \sim 11 \text{ mm} \) (see Fig. 5). When the projectile was fired on a 20 mm thick plate, it penetrated to a depth of 18 mm and then rebounded back. As in MS3 plates, the front-side crater diameters in RHA plates were greater than the diameters at their rear side; however, now the material is very hard and the jacket is more easily stripped than for MS3 plates and, therefore, the entry diameter decreases with increase in thickness. The exit diameters tend to be equal to the core diameter. The values of entry and exit diameters are plotted in Fig. 3.

The impact and residual velocities of the projectile are given in Table 2 and are plotted against plate thickness in Fig. 4.

3.3. Aluminium plates

The thicknesses of aluminium plates employed in the present experiments were 6.1 mm (AL1); 20 mm (AL2); and 10, 20, 30 and 40 mm (AL3). These plates had hardnesses of 90–92, 95–100 and 30–35 VPN, respectively.

![Graph showing crater diameter versus plate thickness for MS3, RHA, and AL3 plates.](image)
In these experiments, it was found that the diameters of the crater formed in AL3 were 8.1 mm on the front and 7.5 mm on the rear side.

Craters on the front side of AL3 plates showed the formation of very small petals as compared to the ones formed in mild-steel plates (MS3), and a light bulge was seen on their rear side. In these plates, the diameters of the craters formed were of larger size at the rear side than those at the front. This is quite opposite to the response of mild-steel plates (MS3) where the front-face crater diameters were larger. This is because the jacket itself begins to perforate, and with increase in thickness, the jamming is more and the debris coming out along with the core at the exit increases the diameter there. This happens up to a particular plate thickness, beyond which the diameter at the exit begins to decrease.

Fig. 2 ((c) and (d)) shows the typical front and rear damages of a 30 mm thick aluminium (AL3) plate along with the MS3 plate for comparison. The crater diameters are plotted against thickness in Fig. 3.

The impact and residual velocities measured in the tests on all the plates are given in Table 2. The residual velocities for plates of AL3 are plotted against the plate thickness in Fig. 4.

In the following section, an analysis of these results is presented and an attempt is first made to determine $r^*$ - the thickness of the plate of each material for which the incident velocity is the ballistic limit. Relations are then developed to determine the residual velocity for the plate of thickness $r < r^*$.

The maximum thickness of the AL3 plates was 40 mm. The residual velocity for this plate was 593 m s$^{-1}$. To be able to determine $r^*$, plates of higher thickness were not available. Experiments on layered plates reported in Section 4 later, however, show that, for plates of thickness greater than $r^*/4$,
their layers in contact give nearly same residual velocity as obtained for a single plate of the same total thickness. Fig. 4, therefore, includes some such results for AL3, to help determine \( t^* \) from extrapolation of the residual velocity–plate thickness curve.

### 3.4. Analysis of Results

From the results of experiments on MS3, RHA and AL3, as given in Table 2, and the curves in Fig. 4, the residual velocity of the projectile for a normal incidence can be written in the form

\[
V_r = V_i - Kr^2,
\]

where \( V_i \) and \( V_r \) are the incident and residual velocities, \( r \) is the plate thickness and \( K \) is a function of both plate material and the impact velocity. Experiments on varying impact velocities are in progress and will be reported in a future paper. The values of \( K \) for different materials, as determined from the present experiments at the impact velocity of \( \sim 820 \text{ m s}^{-1} \), are 0.17, 1.05 and 2.53 for AL3, MS3 and RHA plates, respectively.

From Eqn (3), the thickness \( r^* \), for which the incident velocity \( V_i \) is the ballistic limit for different materials, may be found by substituting \( V_r = 0 \), the respective values of \( V_i \) and \( K \) as determined above. For \( r = r^* \), and \( V_r = 0 \), from Eqn (3) we get

\[
r^* = \sqrt{\frac{V_i}{K}}
\]

The values of \( r^* \) were found from Eqn (4) for AL3, MS3 and RHA as 70, 28 and 18 mm, respectively.

Now, substituting for \( K \) from Eqns (4) and (3) can alternatively be written in the form

\[
V_i = V_i \left[ 1 - \left( \frac{r}{r^*} \right)^2 \right].
\]

Residual velocities of projectiles for different thicknesses of these plates were computed using Eqn (5) for the respective values of thickness \( (r^*) \), for which the incident velocity is the ballistic limit. These are plotted as firm lines in Fig. 4, and are seen to be in good agreement with the experimental results. Eqn (5) is very useful in determining the residual velocity \( (V_r) \) for a thickness, \( r < r^* \), when the plate thickness \( (r^*) \) is known.

The hardness of the materials used in the present experiments have been plotted against the respective \( r^* \) in Fig. 6. This also contains a point from oblique impact on 20 mm thick aluminium plate (AL2), as discussed later (see discussion on oblique impact). From these results, \( r^* \) has been related to the hardness \( (H) \) of the material, by a relation of the form

\[
\ln(r^*) = 6.65 - \frac{2}{3} \ln(H).
\]

Eqns (5 and 6), when employed together would give the residual velocity in terms of the hardness of the

![Image](https://example.com/fig6.png)

**Fig. 6.** Hardness of material versus thickness \( r^* \), for which impact velocity is ballistic limit.
material. Now, for MS1, the hardness is 115 VPN and the incident velocity is \( \sim 820 \text{ m s}^{-1} \). We determine from Eqn (6), the value of \( r' \) (=33 mm). For \( t = 4.7 \text{ mm} \), from Eqn (5), we get \( V_r = 804 \text{ m s}^{-1} \). The experimental value is 759 m s \(^{-1}\).

For MS2, however, the incident velocity is \( \sim 865 \text{ m s}^{-1} \) and its hardness is 150 VPN. From Eqns (6 and 4), the corresponding \( r' \) is determined as 33 mm. From Eqn (6), for \( t = 6 \text{ mm} \) of MS2, we get \( V_r = 782 \text{ m s}^{-1} \), whereas the experimental value is 792 m s \(^{-1}\).

Similarly, in the case of aluminium of thickness 6.1 mm (AL1) and 20 mm (AL2), from Eqn (6), we get the values of \( r' \) as 38 and 36 mm, and their residual velocities computed are 813 and 576 m s \(^{-1}\), respectively, while the corresponding experimental values are 786 and 614 m s \(^{-1}\), respectively.

For the present thicknesses of the plates and the incident velocities, the relations developed seem to be valid for determining the residual velocity to within 6%.

4. NORMAL IMPACT ON LAYERED PLATES

These experiments were performed to evaluate the response of layered plates of the three lots of mild steel and three lots of aluminium under the normal impact of the given armour-piercing projectile. Impact and residual velocities were measured with a view to compare the data with those of single plates of equal thickness.

<table>
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<th>Layer configuration</th>
<th>Spacing (mm)</th>
<th>Impact vel. (m s (^{-1}))</th>
<th>Residual velocity (m s (^{-1}))</th>
<th>Computed (^*) residual velocity (m s (^{-1}))</th>
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* Computed using Eqns (5 and 6) for single plate of equal thickness.
4.1. Mild steel plates

MS1 plates were 4.7 mm thick and their hardness was of the range 110–115 VPN. The plates were kept in contact and the number of layers were increased in each successive test from one to six. The projectile perforated all the layered configurations and its impact and residual velocities were measured in each case; these are given in Table 3.

The projectile axis remained normal to the plates, as was seen from the perforation location on the target and on the two velocity screens kept at the back of the target. Small petals were observed on the impacted side of the front plate and extrusion of material was seen towards the distal side of the rear layers, as shown in Fig. 7. It was observed that the hole diameter on the impacted side increased as the number of layers increased from one to three, and then decreased with further increase in the number of layers. This behaviour is similar to the single plates of MS3. The exit diameter was smaller than the diameter at the entry point of the plates. Fig. 8 shows photograph of the front and rear crater damages in a three-layered configuration.

The residual velocity of the projectile when fired on different configuration is plotted against total combined target thickness in Fig. 9. Using Eqn (6), it is found that the ballistic-limit thickness \( t^* \) of a single MS1 plate would be 33 mm. Using Eqn (5), the theoretical values of residual velocity for a given single-plate target of equal thickness have been computed (see Table 3) and plotted (see Fig. 9). It is observed that the theoretical calculations using Eqn (5) overestimates the value of residual velocity for a single plate of MS1 by \( \sim 6\% \) and underestimates for other layered configurations by a varying amount and up to a maximum of \( \sim 25\% \) when we have six layers. The total thickness \( (t^*) \) for the layered configuration of plates is found from experiments as 36 mm, i.e. \( \sim 9\% \) higher than the \( t^* \) value for a corresponding single plate.

Fig. 7. Deformations in layered plates of mild steel (MS1).
Fig. 8. Photograph showing crater damages in three-layered mild steel (MS1) plates in normal impact: F - front; and B - rear.

Fig. 9. Residual velocity versus target plate thickness in normal impact of layered plates of MS1, MS2, MS3 and AL1, along with the results for the corresponding single plate.

MS1 plates were also kept in three layers, with spacing between the layers, to study the ballistic resistance of the combined target due to gap. The spacings were 30 and 40 mm in successive tests. It was observed that the residual velocity of a three-layered configuration was 636.6 m s$^{-1}$ when the layers were kept in contact, and it was 652 and 675 m s$^{-1}$ when the gaps between each consecutive layer were 30 and 40 mm, respectively.
Layers of up to six mild steel (MS2) plates of 6.0 mm thickness were subjected to normal impact at a velocity of \( \sim 865 \) m s\(^{-1}\). The impact and residual velocities were measured in each test and are given in Table 3 and plotted in Fig. 9. The projectile perforated all the layered configurations. The deformed plates showed extrusion mode of deformation on the distal sides of the rear layers.

The crater diameter on the impacted side of the first layer in all the configurations varied in the range 10.7–12.0 mm. The crater diameter on the rear side of last layer decreased from 13.0 mm for a single-layered to 6.1 mm in a six-layered configuration.

Using Eqn (5), the theoretical values of residual velocity in case of monolithic plate of equivalent thickness have been computed (see Table 3) and plotted in Fig. 9. These theoretical results overestimate the value of residual velocity for a single plate by \( \sim 5\% \) and underestimates the values for all other layered configurations by a maximum of \( \sim 20\% \). The experimental \( \hat{v} \) in the case of MS2 layered plates is 37 mm, whereas the value of \( \hat{v} \) determined from single-plate consideration is 33 mm, i.e. \( \sim 12\% \) higher.

Mild steel plates (MS3) of thicknesses 10, 16, 20 and 25 mm were generally put into two layers and were impacted normally at a velocity of impact of \( \sim 820 \) m s\(^{-1}\).

Impact and residual velocities of the projectiles when impacted on the above-mentioned configurations are given in Table 3 and plotted in Fig. 9. The results reveal that there is no significant change in the ballistic performance due to layering of these plates in comparison to equivalent monolithic plate.

Tests were also carried out to study the ballistic performance of layered plates when the combined thickness of the layers exceeded the ballistic-limit thickness, and some results are presented in Table 3. For this, 10, 16, 20 and 25 mm thick plates were placed in different combinations of two layers. It was observed that in all cases, when the front plate was thinner than the rear plate, the projectile got embedded into the plates. Whereas, when the thicker plate was in the front, the projectile penetrated to \( \sim 28–29 \) mm and then rebounded back. For example, when a 10+20 combination was impacted, the projectile penetrated 28.9 mm and got embedded in the target. Whereas, when the same combination was reversed to 20+10, the projectile penetrated to 26.6 mm and then rebounded back. The phenomenon, due to the stress-wave effects, which have not been analyzed here, is quite interesting and needs further investigations.

For a three-layered target of 10 mm thick plates in contact, it was found that the projectile got embedded. However, when the gap between plates was kept at \( \sim 15 \) mm, the residual velocity was 242 m s\(^{-1}\).

4.2. Aluminium plates

Aluminium plates of 6.1 mm (AL1) thickness were kept in contact in layers, and the number of layers was increased from one to six in each consecutive test. Post-impact measurements were carried out on each plate to study the crater damages and were photographed. It was found that the material showed an extrusion mode of deformation on the distal sides of all the plates and bending in the rear plates (see Fig. 10). The crater diameter of the impacted side of the first layer in all the configurations remained constant, with an average value of \( \sim 8 \) mm.

It was observed that the diameter of the rear crater first increased from 7.5 mm in a single layer to 30.5 mm in a three-layered configuration and then decreased to 6.1 mm in a six-layered configuration. Bulging and dishing were observed in all the layers. In all the layered configurations up to five layers, the rear side crater diameter increases from the first to the second layer, and then gradually begins to decrease in all the subsequent layers. But in the six-layered configuration, it was observed that the rear side crater diameter decreased gradually from 10 mm in the first layer to 6.1 mm in the last layer. Photographs of the front- and rear-crater damage of plates in a four-layered configuration kept in contact are shown in Fig. 11.

The impact and residual velocities are given in Table 3 and are plotted against total combined target thickness in Fig. 9. Using Eqn (6), for a hardness of 90 VPN, it is found that the ballistic-limit thickness \( \hat{v} \) of these AL1 plates would be 38 mm. Using Eqn (5), the theoretical values of residual velocity for a single plate of equal target thickness have been computed (see Table 3) and plotted (see Fig. 9). It is observed that the theoretical calculations using Eqn (5) overestimates the value of residual velocity for single plate and underestimates for all other layered configurations. This shows that due to layering of such thin plates, the ballistic efficacy of a combined target is rather far less than that of a monolithic
Fig. 10. Deformations in layered plates of aluminium (AL1).

Fig. 11. Photograph showing crater damages in four-layered aluminium (AL1) plates in normal impact: F – front; and B – rear.
plate of equivalent thickness and material. The total thickness ($t^*$), from the experiments, for layered AL1 plates would be 60 mm, i.e. ~50% higher when compared to that of a single-plate $t^*$ of the same material.

Two-layered AL1 plates were also tested for their ballistic performance by spacing the layers by 20 and 30 mm. The residual velocity of a two-layered AL1 kept in contact was 743.7 m s$^{-1}$ and it increased to 760.5 and 801.3 m s$^{-1}$ when the gap was 20 and 30 mm, respectively.

Two layers of AL2, with a total thickness of 40 mm, were impacted at 820 m s$^{-1}$ and it was found that the projectile penetrated up to just short of full length and remained embedded. Thus, the response of the layered target is almost the same as that of the single plate; $t^*$ in this case was found to be 36 mm from Eqn (6) for a single plate.

Aluminium plates of thicknesses 20, 30 and 33 mm were generally put in two and three layers in contact. These plates, having hardness of 30–35 VPN, were impacted normally at a velocity of impact of ~820 m s$^{-1}$, and the impact and residual velocities of the projectile were recorded; these values are presented in Table 3. The results reveal that there is no significant change in the ballistic performance due to layering of such plates of intermediate thickness.

Thus, it is seen that the plates MS3, AL2 and AL3 are equally efficient when layered as the corresponding single plates. However, the thinner plates, MS1, MS2, and AL1 are less efficient when layered. Plates of all thicknesses and materials employed in the present tests are less efficient when layered with space in between than layers in contact. The data of the layered configurations of MS3, AL2 and AL3, therefore, could be used to supplement data of single plates for determining $t^*$ from the extrapolation of residual velocity–plate thickness curves.

5. OBLIQUE IMPACT ON SINGLE PLATES

Experiments were performed wherein the projectile was fired at an angle of obliquity on single plates of mild steel (MS3) and aluminium (AL1 and AL3). The angle of obliquity was increased gradually from 0° (normal impact) to 60° or till ricochet occurred in each plate. Measurements of the impact and residual velocities were obtained. The velocity drop in the projectile and influence thereon of the plate thickness and the angle of impact obliquity are presented. The influence of plate thickness and the angle of obliquity on both the ballistic limit and the ricochet is discussed. The angle of exit of the projectile after perforation of the plate was measured for each plate, at all angles of impact.

5.1. Mild steel plates

PROJECTILES were fired at different angles of oblique impact on mild steel plates (MS3) of 10, 12, 16, 20, and 25 mm thickness. For all the plate thicknesses of mild steel, it was observed that the craters formed after perforation or ricochet were all elliptical in shape. The impact and residual velocities were measured in each case and are given in Table 4. From these values, the percentage non-dimensional velocity drop, as defined by Goldsmith and Finnegan [27], was computed in each case as

$$V_d = \frac{V_i - V_R}{V_i} \times 100$$ (7)

The computed values of velocity drop are also tabulated in Table 4. The plots of $V_d$ versus the angle of impact for various plate thicknesses are shown in Fig. 12. Each point in Fig. 12, which correspond to a 100% velocity drop, gives the ballistic limit angle for each plate thickness.

When the projectile was fired at an angle greater than the angle for ballistic limit, a stage came when the projectile penetrated the plate and came out of it from the impacted side itself. The minimum angle at which this occurs is called the critical ricochet angle ($\theta_c$). Fig. 13 shows photographs of 12 and 20 mm thick plates, deformed due to the projectile impacted at angles of critical ricochet, which were 59° and 51°. When the target plate was impacted at an angle of obliquity greater than $\theta_c$, the projectile ricochet occurred without penetration. It was observed that a projectile, fired at an angle less than the angle of critical ricochet and greater than the angle at which perforation takes place, embeds into the target.
Table 4. Measured impact and residual velocities and angles of projectile on oblique impact of mild steel (MS3) plates

<table>
<thead>
<tr>
<th>Plate thickness</th>
<th>Angle of obliquity (Deg.)</th>
<th>Impact velocity (m s⁻¹)</th>
<th>Residual velocity (m s⁻¹)</th>
<th>Non-dimensional velocity drop (%)</th>
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</thead>
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* Critical ricochet angle.

Fig. 12. Non-dimensional velocity drop versus angle of impact for different plate thicknesses of mild steel (MS3).

When the projectile perforates the target at an oblique angle of impact, it has been observed in the present experiments that the projectile does not come out of the rear side of the plate in the same straight path, but tends to turn towards or away from the normal to the plate depending on the angle at which it strikes the plate, its material and the thickness of the plate. The angles of exit of the projectile for different angles of impact for various plate thicknesses are given in Table 4, and the plots are shown in Fig. 14.
Fig. 13. Photograph showing crater damage in a 20 mm thick mild steel (MS3) plate due to critical ricochet of projectile.

Fig. 14. Angle of exit versus exit angle of impact of projectile for different plate thicknesses of mild steel (MS3).

5.2. Aluminium plates

For aluminium plate of thickness 20 mm (AL2), it was observed that the projectile perforated the plate till the angle of obliquity was increased to 45°; but for the incident angle of 52°, the projectile ricocheted. The impact and residual velocity of the projectile are given in Table 5.

Experiments on aluminium plates of 10, 20, 30 and 40 mm thickness (AL3), showed that the projectile perforated all the plates at all the angles of oblique impact up to 60°.

Measurements of the impact and residual velocities were carried out and are tabulated in Table 5. The non-dimensional velocity drop in each case was computed using Eqn (7) and the values obtained are given in Table 5. The plots of $V_d$ versus the angle of impact for different plate thicknesses are shown Fig. 16. The points in Fig. 15, which correspond to the extrapolated 100% velocity drop, gives the ballistic-limit angle for each plate thickness.
Table 5. Impact and residual velocity and angles of projectile in oblique impact on aluminium plates AL2 and AL3

<table>
<thead>
<tr>
<th>Material</th>
<th>Target thickness (mm)</th>
<th>Angle of obliquity (Deg.)</th>
<th>Impact Velocity (m s⁻¹)</th>
<th>Residual velocity (m s⁻¹)</th>
<th>Non-dimensional velocity drop (%)</th>
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</table>

Fig. 15. Non-dimensional velocity drop versus angle of impact for different plate thicknesses of aluminium (AL3).

The craters formed after perforation were elliptical in all the plates. The angles of exit of the projectile for different angles of impact in various thicknesses are given in Table 5 and are plotted against their respective angles of impact for different thicknesses of target in Fig. 16.

A plot of the residual velocity versus the actual path traversed is shown in Fig. 17. This shows that the residual velocity is close to the corresponding value determined for a single plate of thickness equal to the actual path traversed (and not sec θ) in oblique impact, for MS3 and AL2 plates for incident angles of up to 45°, if perforation takes place. However, for AL3 plates, this is true only for 30 and 40 mm thick plates when impacted at 30° and 45°.

5.3. Analysis

From the values of the residual velocities measured in the present experiments on mild steel plates (MS3) and aluminium (AL3), as given in Table 4, the percentage non-dimensional velocity drop in each
case is computed using Eqn (7) and plotted against the angle of impact for various plate thicknesses, as shown in Figs 12 and 15. From these results, the non-dimensional velocity drop \( V_d \) can be written as

\[
V_d = \exp(K_2\theta) + K_3,
\]

where \( \theta \) is the angle of obliquity and \( K_2 \) and \( K_3 \) are functions of plate thickness \( t \). The value of \( K_3 \) is determined by considering that for normal impact \( (\theta = 0^\circ) \), Eqn (8) becomes

\[
(V_d)_0 = 1 + K_3.
\]

Hence,

\[
K_3 = (V_d)_0 - 1,
\]

where \((V_d)_0\) is the velocity drop in the normal impact. Now, from Eqn (3) we get

\[
V_i - V_R = Kt^2,
\]

or

\[
(V_d)_0 = \frac{V_i - V_R}{V_i} \times 100 = \frac{K}{V_i} t^2 \times 100.
\]
For mild steel, \( K = 1.05 \), and for \( V'_1 = 820 \, \text{m} \, \text{s}^{-1} \)

\[
(V'_{0})_0 = 0.128 \times r^2. \tag{13}
\]

The points in Fig. 12, which correspond to the 100% velocity drop, give the ballistic-limit angle for each plate thickness. For the present projectile velocities of \( \sim 820 \, \text{m} \, \text{s}^{-1} \), the angle in degrees \( (\theta_b) \) for the ballistic limit to occur in a mild steel (MS3) plate of thickness \( t \) is given as

\[
\theta_b = K_3 \times \left( \frac{1 - r^*}{r^*} \right)^{\frac{3}{2}}. \tag{14}
\]

where \( r^* \) is the thickness for which the impact velocity \( V'_1 \) is the ballistic limit in the normal impact, i.e. when \( \theta_0 = 0^\circ \).

For mild steel, it is found that \( K_3 = 70^\circ \). Substituting for \( K_3 \) from Eqn (10) and for \( \theta_b \) – the obliquity for ballistic limit for each thickness (for \( V'_d = 100\% \)) – from Eqn (14), the value of \( K_2 \) for each thickness is obtained as

\[
K_2 = \frac{\ln(100 - K_3)}{\theta_b}. \tag{15}
\]

With the help of Eqns (13–15 and 18) was solved to give the non-dimensional velocity for any given thickness for which perforation takes place. The equations are valid up to the thickness for which the impact velocity \( V'_d \) becomes the ballistic limit. The results thus computed for the velocity drop compared very well with the experimental results, as shown in Fig. 12.

In the present experiments on aluminium plates (AL3), all the plate of thickness up to 40 mm were perforated by the projectile at all the angles of impact obliquity up to 60°. Hence, the angle \( \theta_b \) for ballistic limit to occur in aluminium plates of different thicknesses could not be found experimentally.

Eqn (8) can be written as

\[
K_2 = \frac{\ln(V'_d - K_3)}{\theta} \tag{16}
\]

and Eqn (15), as

\[
\theta_b = \frac{\ln(100 - K_3)}{K_2}. \tag{17}
\]

From Eqns (16 and 17), \( \theta_b \) can be written as

\[
\theta_b = \frac{\ln(100 - K_3)}{\ln(V'_d - K_3)} \theta. \tag{18}
\]

Values of \( \theta_b \) computed from Eqn (18) are 78°, 77.5°, 77° and 75° for plates of thicknesses 10, 20, 30 and 40 mm, respectively.

Non-dimensional velocity drop \( V'_d \) is obtained from Eqn (8) for \( K_1 = 0.17 \) for AL3, and using Eqns (9 and 15). The results are presented in Fig. 15 along with the experimental results.

6. CONCLUSIONS

The paper provides data for normal and oblique impact on single and layered plates for a jacketed hard-core projectile at an impact velocity of \( \sim 800-880 \, \text{m} \, \text{s}^{-1} \). Simple relations are presented to approximate the thickness \( t' \) of the plate of given material for which the incident velocity is the ballistic limit. Once \( t' \) is known, the residual velocity for a plate of thickness \( t < t' \) may be obtained from the relations developed.

It is seen that for relatively thick plates (with \( t > t'/4 \)) in two layers, the residual velocities seem to be comparable to the single plates of equal thickness. However, when the plates are thin, \( t < t'/4 \),
the layered combinations in contact give higher residual velocity for the plates of both the materials tested. For spaced targets, of all materials, the residual velocity was higher than the plates in contact.

For RHA steel plate of 20 mm thickness, the projectile penetrated by ~18 mm and then it rebounded back. For two-layered targets of mild steel (MS3), when the total thickness was greater than the front layer was thinner than the rear layer. However, when the front layer was thicker, the projectile penetrated up to ~29 mm and rebounded back. This phenomena is of interest and calls for further investigation.

In oblique impact, it is seen that the angle of exit is smaller or greater than the angle of incidence depending on the thickness of the plate and hardness of its material.

For MS3 and AL2 plates, it was seen that the residual velocities in oblique impact compared well with the residual velocities for single plates of thickness equal to actual path traversed for incidence angles of up to ~45°. For AL3 plates, these values compared well only for 30 and 40 mm plates for incidence angles of 30° and 45°.

REFERENCES


