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Lip Height and its Significance in Ballistic Studies

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ABSTRACT

The mechanism of lip formation in steel armour plates has been investigated. Low alloy steel armour plates of 20, 40 and 80 mm thickness were impacted at zero incidence by steel projectiles of 6.1, 20 and 40 mm diameter, respectively at different velocities. The lip height was observed to exhibit definite correlations with other ballistic parameters like depth of penetration, crater volume, plastic zone and kinetic energy of the projectile.

1. INTRODUCTION

The ballistic performance of an armour system is related to its energy-absorbing capacity during projectile—target interaction. The nature of plate-projectile deformation during this interactive period is governed mainly by a number of ballistic parameters related to the plate and the projectile. Density, shape, size, strength and velocity of the projectile and density, strength, thickness and obliquity of the plate are such important primary ballistic parameters. The overall interactive behaviour of these primary parameters ultimately dictates the mechanism of penetration and/or perforation in an impact-related event. For the purpose of studying such a mechanism or for establishing the ballistic worth of the armour plates, some resultant parameters are required to be determined experimentally. Depth of penetration (X_p), volume of crater (U), size of the plastic zone (L) that forms all around the penetrating projectile, bulge height, etc. are such secondary parameters that help in understanding the mechanism of penetration. U is a very sensitive parameter in assessing the plate resistance that is offered against the penetrating projectile[1] and needs to be determined carefully. Determination of L, which is the main source of energy absorption at subordnance velocities, requires sectioned sample of the crater for the purpose of polishing and subsequently determining the hardness profiles. While dealing with heavier plates of large size, this task of cutting each and every crater in the plate and preparing cut samples for the measurement of hardness becomes a very tedious and time-consuming process. To overcome these complexities that arise in the way of determining the resultant parameters, a question arises, whether there exists a parameter that can be measured accurately? Answer to this question is not readily available in ballistic literature. However, in an earlier work[1], a parameter called lip height (H_e), was used. H_e can be measured accurately in a simple way, even while dealing with the plates of very large masses. Lip formation takes place on the entry side of the thick plate due to pushing back of the plate material along the side walls of the projectile. What is really required to be seen is whether H_e can be used to estimate those secondary

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parameters, so that the time-consuming process involved in the measurement of such parameters can be avoided.

This paper is aimed to show whether H_e measured on the entry side of the thick steel armour plate at zero incidence exhibits a definite correlation and can thus be used to estimate the X_p, U and L in plate-projectile combinations having different T/D ratios, where T is the plate thickness, and D the projectile diameter.

2. EXPERIMENTAL DETAILS

2.1 Material

Low alloy steel armour plates of thickness 20, 40 and 80 mm in the hot rolled condition were used as the target material. Hardness of the plates was 350, 315 and 295 HV, respectively. The sizes of the plates used were approx 1m . 1m, irrespective of its thickness. Mechanical properties of the steel armour plates used in the present investigation are given in Table 1.

Table 1. Mechanical properties of steel armour plates

Property	Thickness of the plate		
	20 mm	40 mm	80 mm
Vickers hardness (HV) (30 kg load), kg/mm^2	350 ± 10	315 ± 10	295 ±
Yield strength (σ_{YS}), MPa	1080	920	860
Ultimate tensile strength (σ_{UTS}), MPa	1160	1000	960
Strength coefficient (K_o)*, MPa	1500	1400	1285
Strain hardening	0.07	0.087	0.10

σ Flow stress ~ $K_o\varepsilon^n$

ε True plastic strain

Armour piercing steel projectiles of mass 5.2, 110 and 1250 g and of diameter 6.1, 20 and 40 mm respectively were impacted on these steel plates. Details of the projectiles used are given in Table 2.

Table 2. Details of steel projectile

Hardness (HV 30)	Mass (g)	Diameter (mm)	Length to diameter ratio
750		6.1	5.73
600		20.0	2.71
350		40.0	3.87

2.2 Ballistic Test Details

All the ballistic tests were conducted at zero obliquity, i.e. the projectile impacted the plates normally. The 20 mm thick steel plate was impacted by a 6.1 mm diameter steel projectile, the 40 mm thick steel plate by a 20 mm diameter projectile and the 80 mm thick steel plate by a 40 mm diameter projectile. Velocity of the projectile in each case was measured using an aluminium foil digital timer system. During ballistic testing, plates were firmly clamped to the plate holder, though rigidity aspects do not significantly affect the ballistic performance of such armour plates at subordnance velocity[2]. Data on the striking velocity of the projectile for different plate-projectile combinations are given in Table 3.

Table 3. Data on striking velocity of the projectile for different plate-projectile combinations

Plate thickness, T (mm)	Projectile diameter, D (mm)	T/D ratio	Projectile velocity, V (m/s)
80	40.0	2.00	518
80	40.0	2.00	370
40	20.0	2.00	593
40	20.0	2.00	327
20	6.1	3.28	727
20	6.1	3.28	309

2.3 Post-Impact Examination

After the ballistic tests, each crater was subjected to a detailed examination. The impact craters on the target plate were photographed on the entry side. X_p, U and H_e associated with each crater were measured. These parameters are illustrated in Fig. 1. After making the above measurements, selected impact craters were sectioned along their diameter to result in a sectioned surface (Fig. 1). This sectioned surface was then ground and polished in emery paper up to 600 grit. A series of hardness measurements were made on the sectioned surface at regular intervals along the lines Y_1, Y_2, Y_3 and X, as shown in Fig. 1. Using this information, the hardness-distance profile could be determined and in turn the distance up to which L

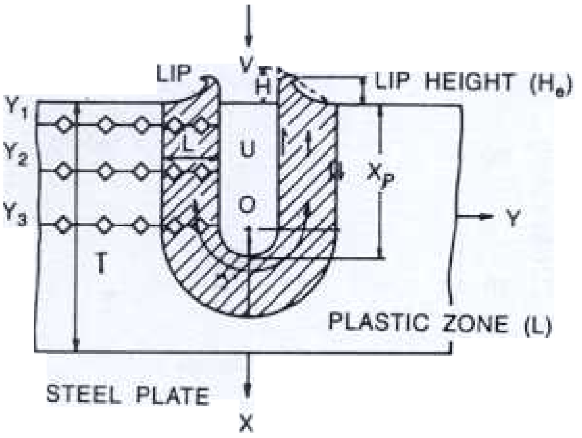

Figure 1. Schematic view of impact crater illustrating the various parameters measured.

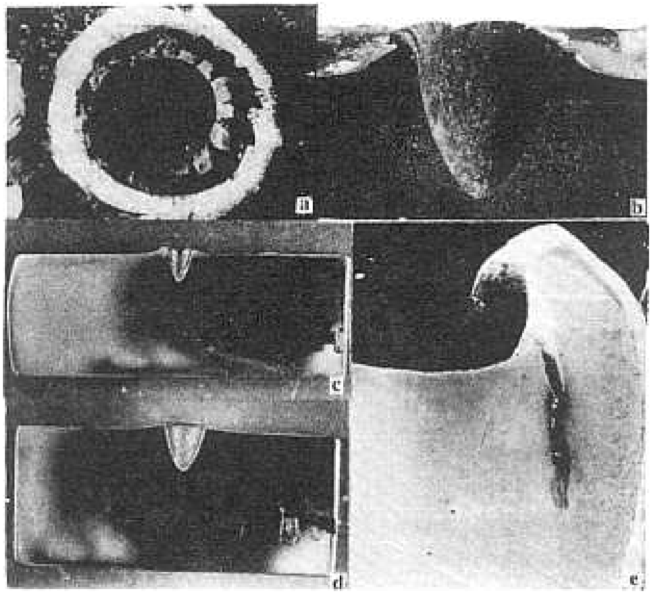

Figure 2. Typical view of the lip formed on the entry side of thick steel plates.

extends from the side walls of the impact crater could be measured.

3. RESULTS

3.1 Appearance of Impacted Plates

Impacted steel armour plates of 20, 40 and 80 mm thickness were examined for assessing the nature and mode of deformation of the plate material. On the entry side, significant lip formation was observed all around the periphery of the impact crater (Fig. 2). This lip was separated at many locations along the circumference, leading to the formation of petals (Fig. 2(a)). Figure 2(b) depicts lip formation in a 80 mm thick plate impacted by a 40 mm diameter projectile. Lip formed by 6.1 mm diameter steel projectile in a 20 mm thick steel plate at low and high velocities is shown in Figs 2(c) & (d), respectively. A magnified view of the lip formed in 40 mm thick steel plate by 20 mm diameter projectile is presented in Fig. 2(e). It was noted that the lip had curled susbstantially. The term H_e in this paper represents the maximum height of the petals from the front face of the steel armour plate. On attaining this maximum height, petals tend to curl downwards (Figs 1 & 7(c)).

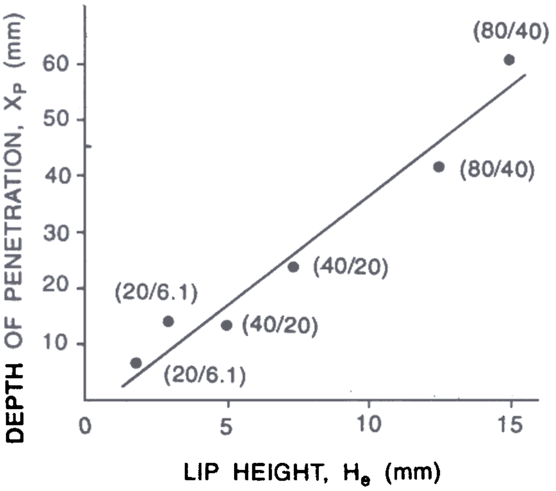

Figure 3. Variation in depth of penetration with lip height in 20, 40 and 80 mm thick steel plates impacted by steel projectiles of 6.1, 20 and 40 mm diameter respectively.

3.2. Depth of Penetration, Crater Volume Plastic Zone Size and Lip Height

The depth up to which the projectile penetrates (Fig. 1) into the steel plate and U created in the process at different striking velocities were measured experimentally. X_p and U increase with increase in velocity of the projectile (Figs 3 & 4). As the projectile penetrates the steel plate, it induces deformation and flow in the plate over an extended region, as illustrated schematically in Fig. 1. In this figure, the shaded region all around the penetrating projectile represents the plastically deformed zone. This plastic zone, also represents the region within which the plate material flows

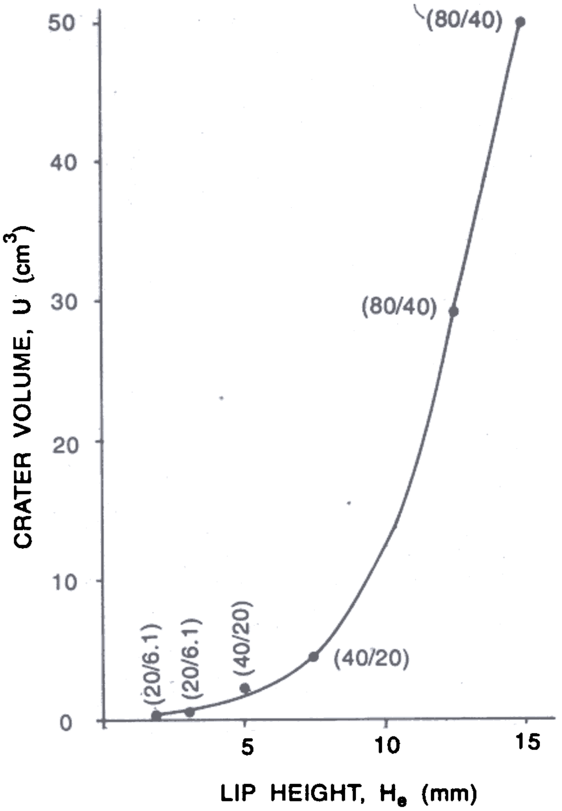

Figure 4. Variation in crater volume with lip height in 20, 40 and 80 mm thick steel plates impacted by steel projectiles of 6.1, 20 and 40 mm diameter respectively.

either backward or forward. The sizes of the plastic zone, as determined from hardness tests for various projectile-target combinations, are given in Fig. 5.

The lip is formed on the entry side of the plate when the plate material ahead of the penetrating projectile is pushed back along the side walls of the projectile. The H_e (Figs 1 & 7(c)) was measured in 20, 40 and 80 mm thick plates at different striking velocities of the projectiles. The trend of variation of projectile energy with H_e is shown in Fig. 6. With increase in energy of the projectile, there is an increase in H_e.

3.3 Correlation with Lip Height

The trend of variation in X_p with H_e is shown in Fig. 3. Data in parentheses represent *T/D* ratio. It is clear that X_p increases in a linear manner with increase in H_e. The trend of variation in U with H_e (Fig. 4) is not similar to the variation in X_p, as seen in Fig. 3. This kind of behaviour is attributed to the shape of the projectile. In the case of 6.1 mm diameter steel projectile, its nose is conical wherein despite the quantity of the back flowing material being much less, there is a sharp increase in H_e. Such a situation can, however, arise only when there is no substantial curling of the lip. From Figs 2(c) & (d), it is evident that the lip has not curled substantially as noticed in the case of 40 and 80 mm thick plates (Figs 2(a) & (e)). The trend of variation in L size with H_e is shown in Fig. 5; it is similar to the variation noticed in the case of X_p (Fig. 3). This is obvious, as X_p and L are interrelated parameters[1]. Variation in K.E. with H_e is shown in Fig. 6. It is evident from Figs 3-6 that H_e relates very well with the X_p, L, U and K.E. in steel armour plates of 20, 40 and 80 mm thickness, when impacted by projectiles of 6.1, 20 and 40 mm diameter at zero incidence, respectively.

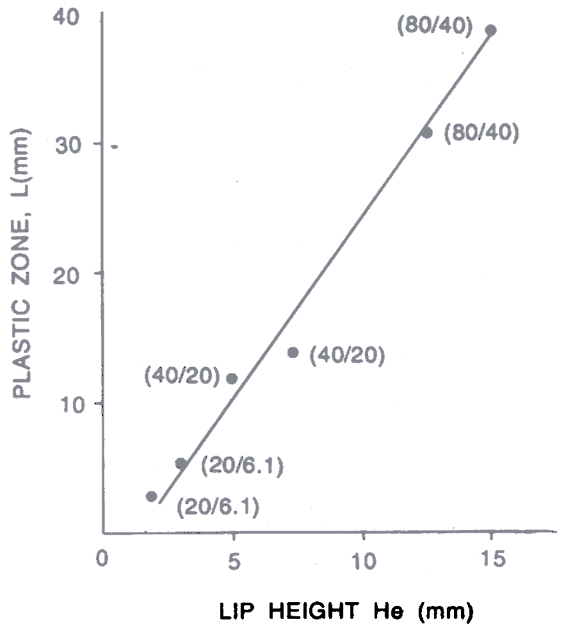

Figure 5. Variation in plastic zone with lip height in 20, 40 and 80 mm thick steel plates impacted by steel projectiles of 6.1, 20 and 40 mm diameter, respectively.

The correlations of H_e with other parameters like X_p, U, L and K.E. can be expressed in the following form:

(a) Depth of penetration and lip height

$$X_p = 3.8\ H_e - 2.50$$

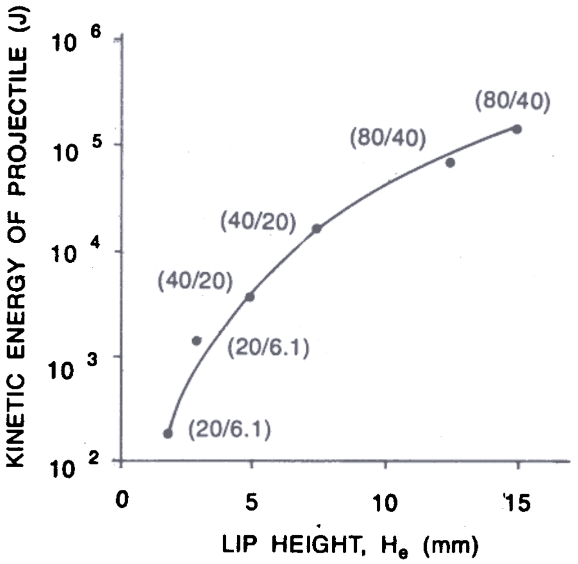

Figure 6. Variation in kinetic energy with lip height in 20, 40 and 80 mm thick steel plates impacted by steel projectiles of 6.1, 20 and 40 mm diameter, respectively.

(b) Crater volume and lip height

$$U = 0.15\, e^{0.41 H_e}$$

(c) Plastic zone and lip height

$$L = 2.75\, H_e - 3.80$$

(d) Energy and lip height

$$\text{KE} = 33.11\, H_e^{3.12}$$

Variation in X_p and L with H_e is observed to be linear, whereas the variation in U and K.E. with H_e is nonlinear. H_e, an often neglected parameter in ballistic studies, has thus been found to be an effective tool in facilitating ballistic experiments and analysis.

4. DISCUSSION

The main theme of this paper is that H_e, an easily measurable parameter, can be correlated with a host of other parameters like X_p, U and L. The penetration conditions under which such a correlation can be expected are elucidated on the basis of Fig. 7. In this figure, progressive development of the lip on the entry side is illustrated as a function of increasing penetration. Our earlier experiments[1] have clearly indicated that the size of L formed around the penetrating projectile actually increases with increasing penetration (i.e. $L3 > L2 > L1$ in Fig. 7) as long as the L ahead of the projectile is confined, i.e., does not impinge on the backface of the plate. Under such conditions, termed as plane strain penetration conditions, the plate material displaced by the projectile has to necessarily flow back leading to ever increasing lip formation (Figs 7(a), (b) & (c)). However, once L ahead of the penetrating projectile impinges on the back face of the plate, bulge formation is initiated and the plate material displaced by the projectile now moves in the forward direction, leading to no further development of the lip on the entry side. It can be concluded that as long as plane strain penetration conditions are maintained, H_e should definitely correlate with parameters like X_p, U, L and K.E. However, it should be noted that the present findings are not valid for an oblique impact and also not for the high hardness steel armour plates. At high hardness, lip gets detached from the plate.

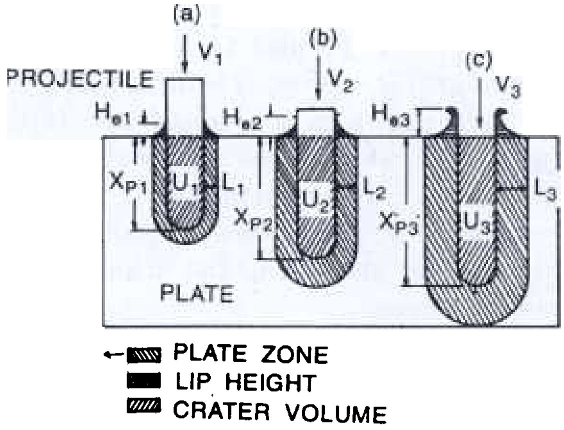

Figure 7. Schematic view indicating growth of plastic zone and lip height with progressive penetration of the projectile into the plate material.

The correlation of H_e with ballistic performance can be considered as a general case so far as plane strain penetration condition prevails in a medium hardness steel armour plate at zero angle of incidence. It should also be considered that in an earlier investigation[1], variation in H_e with striking velocity of the projectile was studied only for a single T/D ratio (T/D = 1). Also, in that study, correlation of H_e with other ballistic parameters like X_p, L, U and K.E. was not studied. In the present work, different projectile-plate combinations have been employed (Table 3) for studying the relationship of H_e with other ballistic parameters so as to present a more generalised case involving different T/D ratios in steel armour plates. Further experimental investigation is needed before correlation of H_e in other armour grade nonferrous materials like aluminium and titanium can be commented upon.

5. CONCLUSION

H_e measured on the entry side of thick steel armour plate at zero incidence exhibits a definite correlation and can be utilised to estimate a host of other relevant ballistic parameters like U, X_p and L that are required for establishing the ballistic worth of steel armour plates with different T/D ratios.

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