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SHORT COMMUNICATION

Ballistic Behaviour of Tempered Steel Armour Plates under Plane Strain Condition

S.N. Dikshit

Defence Metallurgical Research Laboratory, Hyderabad - 500 058.

ABSTRACT

The present investigation deals with the ballistic behaviour of tempered steel armour plates under plane strain condition at normal angle of attack. A conical-shaped steel projectile of 6.1 mm diameter was impacted on 20 mm thick steel armour plates of 350, 450 and 550 Hv hardness, in the velocity range 200 - 700 m/s at zero obliquity. Ballistic performance measured in terms of the depth of penetration indicates that, under plane strain condition, behaviour of 550 Hv steel plate is better than those of the other two plates. However, front spalling causes damage to the entry side of the high hardness plate, thus affecting its multihit capability in a limited manner.

1. INTRODUCTION

Over the years, a number of investigators have attempted to study the influence of hardness on the ballistic behaviour of hardened steel armour plates, impacted at zero obliquity. However, most of the literature data are for thin plates ($T/D << 1$; T = plate thickness and D = projectile diameter) and thus represent hardness effect under plane stress condition. The mechanism of penetration of thick armour plate is related to the confinement of the plastic zone size well within the plate, thus presenting plane strain penetration condition. The plate behaviour under plane strain condition is likely to be different from that under plane stress condition[1], mainly due to absence of bending and stretching of plates. There has been a dearth of investigations, except a few [2], on the effect of plate hardness on the ballistic performance of thick plate ($T/D >> 1$). It is, therefore, essential to study the ballistic behaviour of thick steel armour plates of different hardness, under plane strain condition.

The purpose of this study was to examine the ballistic behaviour of thick, tempered steel armour plates ($T/D >> 1$) at zero obliquity in the subordnance velocity regime.

2. EXPERIMENTAL DETAILS

2.1 Plate Material

A high strength low alloy steel (AISI-4330) of 20 mm thickness, in the hot-rolled condition was used as the target plate.

2.2 Projectile

The projectile used was a 6.1 mm diameter armour piercing steel with a conical nose (Fig.1) and having a mass of 5.2 g. Hardness of the projectile, as measured on a sectioned surface, was 750 kg/mm^2.

2.3 Heat Treatment

Rolled homogeneous armour steel plates of 20 mm thickness were used. Plates were austenitised

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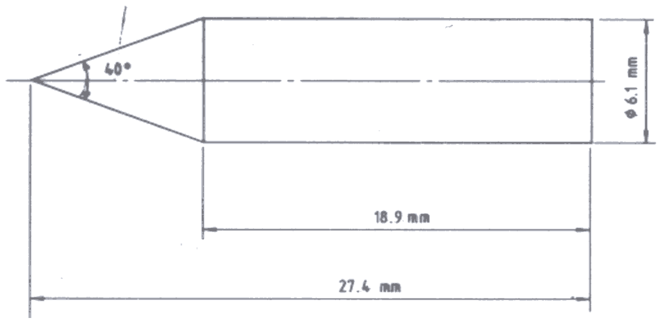

Figure 1. Projectile detail

at 940 °C for 1hr and quenched in commercial grade oil. Plates were then tempered in a furnace and cooled in air. Tempering time and temperature were so selected as to get hardnesses of 350, 450 and 550 Hv in three different plates. Microstructural details are provided in Figs 2 and 3 for 350 and 550 Hv steel plates, respectively. Coarsening of carbide precipitate was visible in 350 Hv plate, leading to reduction in strength and increase in toughness. In comparison, 550 Hv plate had higher strength and lower toughness. Mechanical properties of these plates have been reported elsewhere [2].

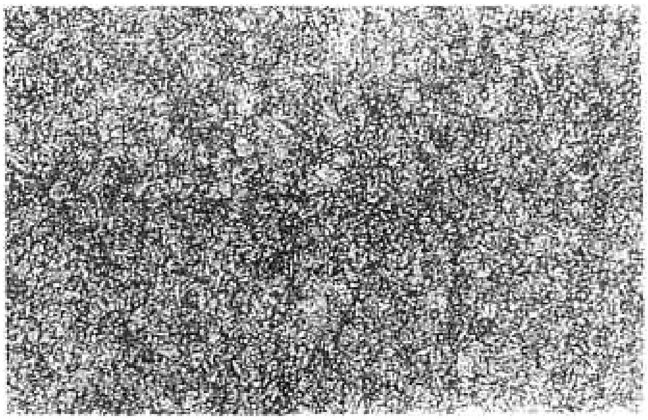

Figure 2. Microstructure of tempered 20 mm thick steel plate at 200 X (350 Hv).

2.4 Ballistic Test Details

Target plates were clamped onto a target holder. However, the manner in which the armour is held during ballistic testing (rigid or non-rigid) had negligible influence on its performance at zero obliquity[3] in the subordnance velocity regime used in the present investigation. The target was kept at a distance of about 25 m from the gun and the gun was firmly secured to the gun mount during the tests. Two screens of aluminium foil (0.01 mm thick) were placed in the path of the projectile at a known distance apart. As the projectile pierced through the first foil, a digital chronometer (1 μs accuracy) was started, and it was stopped when the projectile pierced the second foil. Thus, the time of flight of the projectile between the two foils was determined and its impact velocity (*V*) could be determined. Six to eight shots were impacted on each plate. Variations in impact velocity were achieved by varying the charge mass of the propellant. By proper laying of the gun, it was ensured that the centre-to-centre distance between any two impact craters on the plate was at least three times the diameter of the projectile, so as to ensure that the zones of plastic deformation formed around the crater are not influenced by the earlier ones.

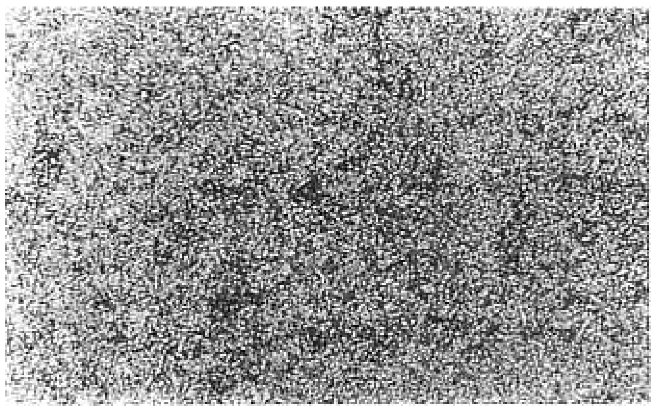

Figure 3. Microstructure of tempered 20 mm thick steel plate at 200 X (550 Hv).

2.5. Post-Impact Examination

Ballistic limit and residual velocity measurements are widely used for assessing the ballistic performance of armour materials. An alternative parameter which characterises very sensitively the resistance of the armour material is related to the deep hole formed by the penetrating projectile. The depth of this hole (*Xp*) and its volume (*U*) are useful parameters in this regard and both these can be evaluated as a function of *V*. *U* provides valuable information with regard to the

Figure 4. Nature of plate damage (entry side) in the 550 Hv plate when impacted by 6.1 mm diameter steel (conical) projectile, at zero obliquity.

average resistance offered by the plate to the penetrating projectile and the type of damage caused.

After the ballistic test, each impact crater was subjected to a detailed examination. First, the impact craters on the target plate were photographed both on the entry and exit sides and the nature of damage caused on the front and rear faces of the plates was examined. *Xp* was measured using electronic digital caliper. *U* was measured by filling the crater up to the original target plate level with plasticine of known density.

3. RESULTS

3.1 Studies on Impacted Plates

The impacted steel plates of 20 mm thickness, tempered at different tempering temperatures, having hardness of 350, 450 and 550 Hv, were

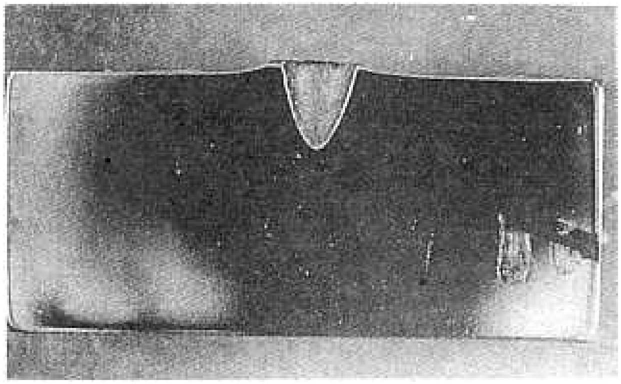

Figure 5. Lip formation on entry side of the 350 Hv plate

examined for assessing the nature and mode of deformation of the plate material during the process of projectile penetration. Magnified view of a selected crater on the front-face of 550 Hv plate is presented in Fig. 4. There is no sign of lip formation on the craters formed in 550 Hv plate at all the striking velocities. This kind of behaviour is attributed to low toughness of this plate. On the entry side, significant lip formation was observed

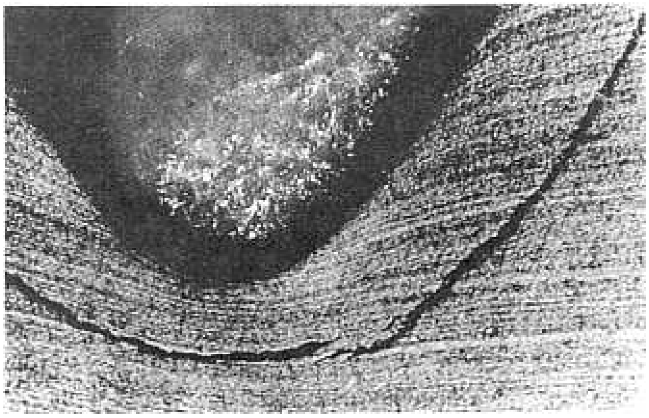

Figure 6. Sectioned surface of a crater on 450 Hv plate showing deep crack around the periphery of the impacted hole by a steel projectile at zero obliquity.

all around the periphery of the impact craters on 350 Hv plate at all the (Fig. 5), indicating higher toughness. Sectioned surface of an impact crater at low magnification (50 X), is depicted in Fig. 6 for a 450 Hv plate. The presence of a deep crack around the periphery of the crater is clearly visible in this figure. The crack is formed in the plastically

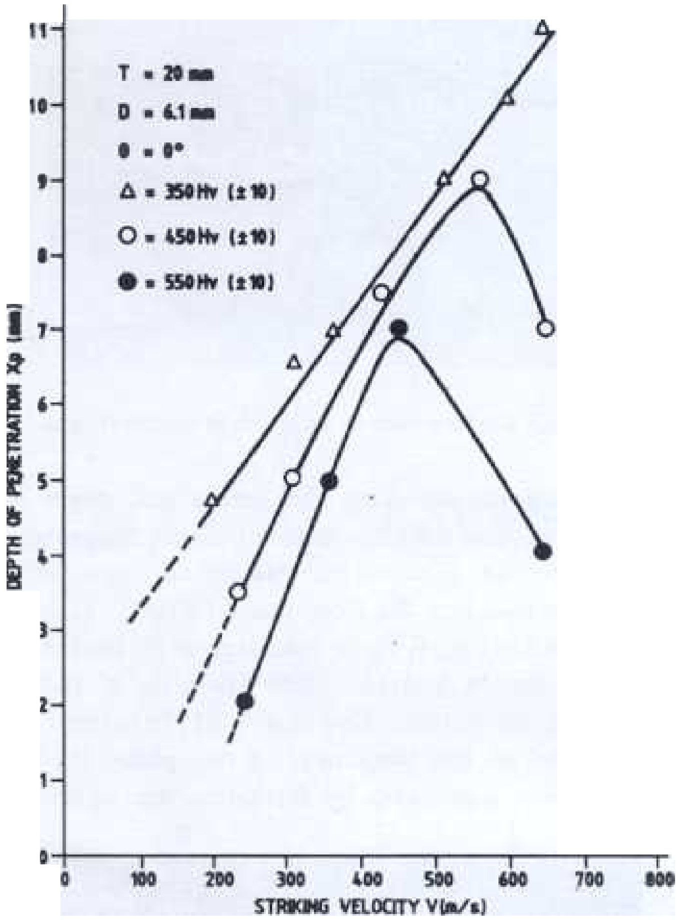

Figure 7. Variation of depth of penetration with striking velocity of 20 mm thick tempered steel armour plates (350, 450 and 550 Hv) at zero obliquity.

deformed zone. Such a crack is not visible in the 350 Hv plate. Even at the highest velocities no bulge was observed on the back-face of the plates. Absence of bulge on the back-face indicates that the plastic zone is confined well within the plate and represents the plane strain condition.

3.2 Depth of Penetration

The depths up to which the projectile penetrates (Xp) into the steel plates of 350, 450 and 550 Hv were experimentally measured over a range of impact velocity (V = 200-700 m/s) and are presented in Fig. 7. The following important observations are made from this figure:

(a) Xp increases monotonically with striking velocity in 350 Hv plate.

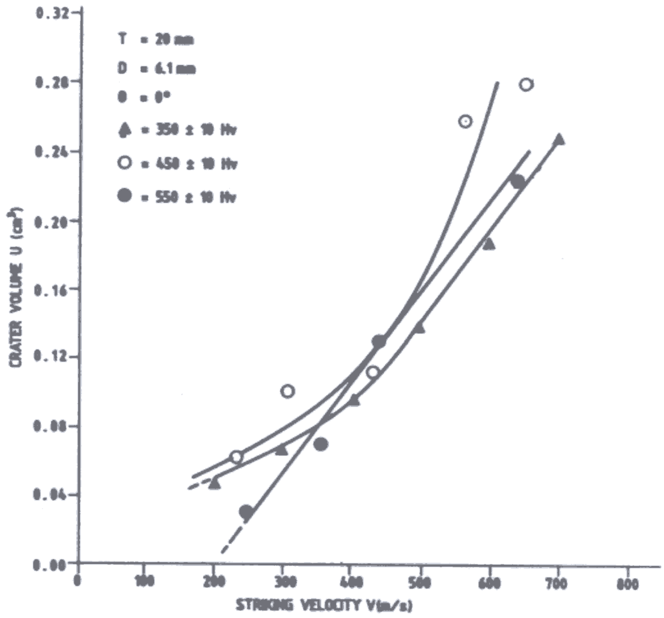

Figure 8. Variation of crater volume with striking velocity of 20 mm thick steel armour plates (350, 450 and 550 Hv) at zero obliquity.

(b) In a 450 Hv plate, Xp increases with striking velocity of the projectile up to V = 550 m/s. At higher striking velocities (V > 550 m/s), there is a dramatic reduction in X_p.

(c) The behaviour of 550 Hv plate is similar to that of the 450 Hv plate except that a dramatic reduction in penetration occurs at about 450 m/s.

3.3 Crater Volume

For all craters, U was computed by filling the blind hole/crater with plasticine of known density. The crater volume data are presented in Fig. 8. Crater volume increases monotonically with striking velocity of the projectile over the entire range of velocities (200-700 m/s). For all impact velocities, U was highest in case of the medium hardness plate (450 Hv). At low striking velocity, U was the least in the case of 550 Hv plate.

3.4 Discussion

It has been observed by some investigators[4] that the projectile will undergo deformation during its penetration into the target plate, if its hardness is less than 1.5 times the hardness of the plate.

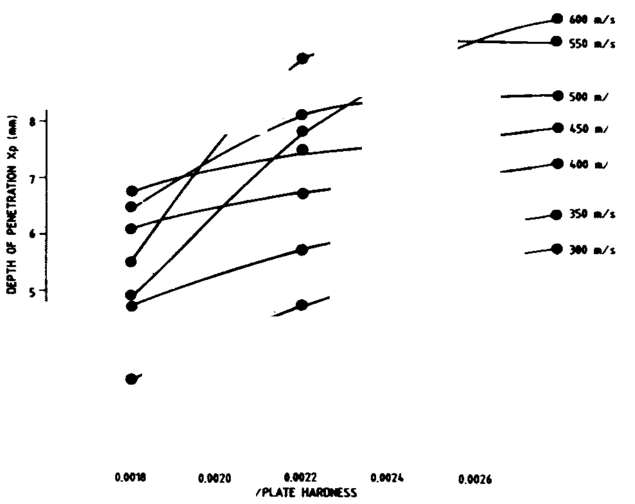

Figure 9. Variation of depth of penetration with 1/ plate hardness.

Figure 7 shows variation in X_p with the striking velocity of the projectile. It is observed that when there is no deformation of the projectile, as with a plate of 350 Hv, the X_p increases continuously with increasing striking velocity. On the other hand, in the case of 550 Hv plate, since the projectile hardness is only 1.36 times that of the plate, a dramatic reduction in X_p beyond a striking velocity of 450 m/s is seen. A 450 Hv plate exhibits an intermediate behaviour in terms of X_p and the tendency to shatter arises beyond a striking velocity of 550 m/s. Higher strength of 550 Hv plate, due to the presence of fine martensitic laths, is the cause for low X_p in the 550 Hv plate. At the same time, it is also known that plates with higher strength offer higher resistance to penetration in the subordnance velocity regime [1], as most of the energy is absorbed in the plastically deformed zone formed around the crater

Crater volume on 450 and 550 Hv plates (Fig. 8) is observed to be more due to front-spalling of these plates. Spalling of the high hardness plate on its front-face is attributed to the onset of adiabatic shear bands (ASBs)-induced plugging phenomenon. A similar observation was made in a related study[2], where 80 mm thick steel armour plate of high hardness was impacted by a 20 mm diameter steel projectile at zero obliquity. Though X_p depth of penetration in 450 and 550 Hv plates is much less than 350 Hv plate, crater diameters are quite large, and this causes more damage to the plate on the entry side. This kind of plate damage due to front-spalling will affect the multihit capability of high hardness plate in a limited manner.

Figure 9 shows variation of X_p with 1/plate hardness at different striking velocities of the projectile. X_p increases with increase in the striking velocity in the case of a plate with low hardness (350 Hv). In the case of high hardness plate (550 Hv), initially penetration increases with increase in striking velocity (up to V = 450 m/s); thereafter, at higher velocities, penetration is reduced in this plate, mainly due to deformation of the projectile[4]. As expected, the ballistic behaviour of medium hardness plate (450 Hv) represents intermediate situation.

4 CONCLUSIONS

- The ballistic behaviour of high hardness steel armour plate (550 Hv) under plane strain condition is better than those of low hardness plates (350 and 450 Hv).
- Damage to the high hardness plates (450 and 550 Hv) on the entry side of the projectile is more, thereby slightly affecting their multihit capability.
- At higher velocities (V 450 m/s), 550 Hv plate causes deformation of the projectile, resulting in drastic reduction in X_p.

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Contributor

Col (Dr) S N Dikshit, VSM, obtained his BE (Metallurgy) from RECW, ME (Mechanical) from Indian Institute of Science, Bangalore and PhD from Banaras Hindu University, Varanasi, in 1970, 1982 and 1994, respectively. At Defence Metallurgical Research Laboratory, he is actively engaged in the design and development of light weight *Kanchan* composite armour and 'explosive reactive armour' for the protection of main battle tanks *Arjun, Vijayanta* and *Ajeya*. He has published several papers in international and national journals. He is a life member of the Indian Institute of Metals. He was awarded *Vishisht Seva Medal* for his meritorious services in the field of armour in 1997.