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SHORT COMMUNICATION

Influence of Hardness on Perforation Velocity in Steel Armour Plates

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ABSTRACT

In an earlier investigation[3], the influence of hardness on tempered steel armour plates of 20 mm thickness, impacted by 20 mm diameter steel ogive-shaped projectile at normal, was studied. Additional data is investigated with relation to the perforation velocity of the plates. It is observed that the plate perforation velocity and the plate plugging velocity decrease with increasing plate hardness.

NOMENCLATURE

σ	Flow stress of plate material
K	Strength coefficient of plate material
n	Strain-hardening exponent
ε	True strain
ε_c	Critical strain required for the formation of adiabatic shear band
ρ	Plate material density
Cp	Specific heat of deforming plate material
C	Temperature coefficient of flow stress
	Fraction of plastic work converted to heat
T	Temperature of the deforming material

1. INTRODUCTION

A limited set of data is available on the effect of plate hardness on ballistic performance of steels. This data[1-2] basically pertains to the thin plates ($T/D < 1$, T = plate thickness and D = projectile diameter). In an earlier work[3], the influence of hardness was investigated when the tempered steel armour plates were impacted by an ogive-shaped steel projectile at normal and such that T/D was 1 and 4. Further, the author has investigated the influence of hardness on the tempered steel armour plates when impacted by a conical projectile at normal[4] and at $T/D \sim 3$. In these investigations, the ballistic performance of tempered steel armour plates was studied in relation to the depth up to which the projectile penetrated the armour plates and also the cumulative specific resistance offered by these target plates since such a study was essential for research purpose. However, from the point of view of assessing the ballistic worth of an armour plate for providing protection to any combat system, it would be more pertinent to know the velocity at which the given armour plate would be perforated. This kind of information is vital for the troops as it describes the upper limit of their risk taking capability. The present work is primarily concerned with the influence of plate hardness on the plate perforation velocity at normal.

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2. BACKGROUND

In the case of thin plates, $T/D < 1$, it was indicated that the ballistic performance of steel armour plate increases with plate hardness to a certain level, beyond which performance actually decreases with increasing hardness[1,2]. Such a decrease in plate performance was attributed to the shear plugging induced by the formation and propagation of adiabatic shear bands (ASBs). It was also observed that if the plate hardness was increased further to approach that of the projectile, its ballistic performance improved, again due to projectile shatter/deformation.

Experimental investigation conducted by the author on tempered steel armour plates[3] to study the influence of the plate hardness on its ballistic penetration at normal and at T/D of 1 and 4 have revealed that increase in hardness of the plate increases the resistance to penetration under plane strain conditions. Whereas, under plane stress condition, as the hardness of plate increases, the resistance to penetration decreases beyond a certain level due to the onset of ASB-induced plugging. The terms plane strain and plane stress indicate confined and unconfined plastic deformation of the target plate, respectively on being impacted by a projectile.

Influence of plate hardness on the ballistic penetration at normal, and when impacted by a conical nose hard projectile with $T/D \sim 3$ had also been investigated by the author[4]. Nose shape of the projectile was changed from ogive[3] to conical[4], and T/D was changed from 1 and 4 to 3 in these investigations[4]. Effect of plate hardness on ballistic penetration was observed to be identical. However, these experimental investigations did not provide information on the influence of plate hardness on the perforation velocity of these tempered plates.

3. EXPERIMENTAL DETAILS

An ogive-shaped steel projectile with 110 g mass and hardness of 650 HV was impacted on the tempered steel armour plates at normal. Quenching and tempering details along with other experimental data are presented in the earlier publication[3]. Low alloy rolled homogeneous armour (RHA) plates were used in the ballistic testing and the ballistic data pertaining to the perforation of the plate has been examined in the present study.

4. EXPERIMENTAL RESULTS

4.1 Plate Perforation

The projectile velocity was varied by varying the charge mass of the projectile. Plate damage after each impact was assessed as of A, B, C, D, E, R and W type based on British Standards 1T-80. In the earlier investigations[3-4], data pertaining to plate damage of A to E type was used in the ballistic penetration studies. In the present case, data pertaining to W-type of damage, i.e., complete penetration /perforation of plate, have been studied.

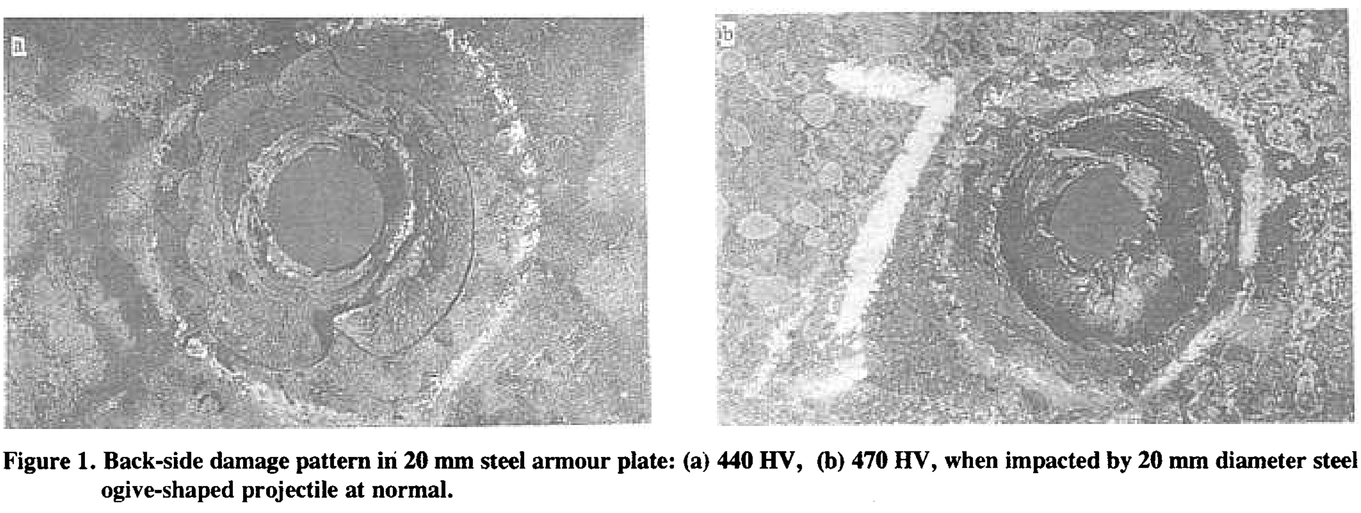

Figure 1. Back-side damage pattern in 20 mm steel armour plate: (a) 440 HV, (b) 470 HV, when impacted by 20 mm diameter steel ogive-shaped projectile at normal.

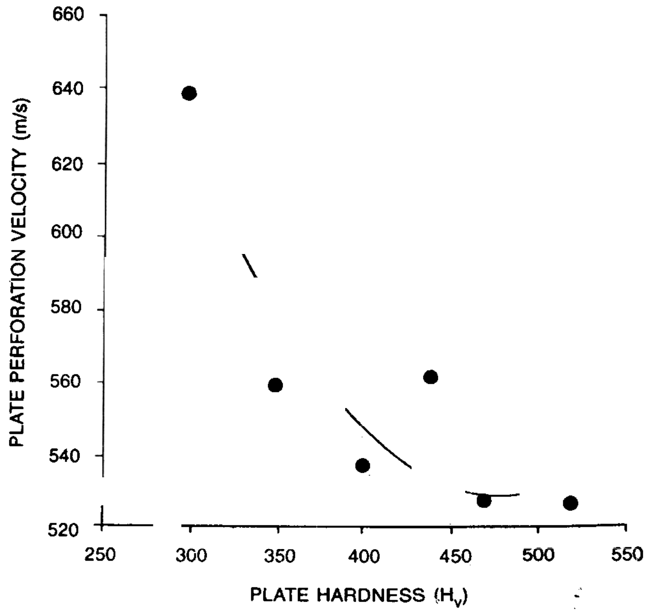

Figure 2. Variation of perforation velocity with plate hardness

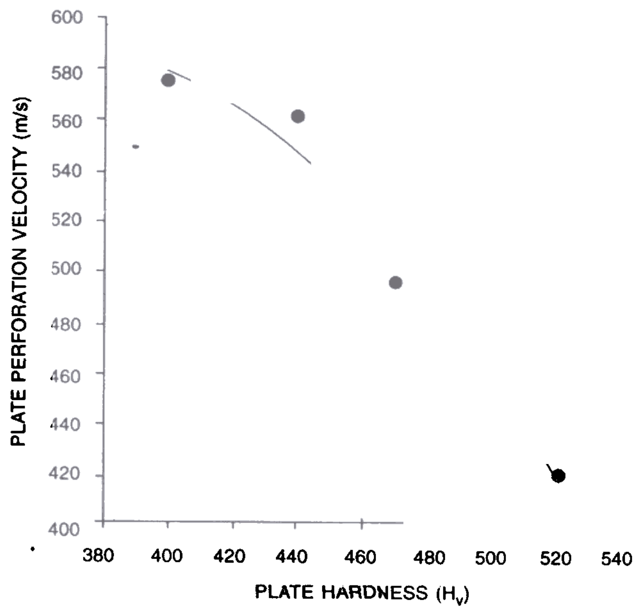

Figure 3. Variation of plugging velocity with plate hardness

As mentioned above, the purpose of this study was to assess the influence of plate hardness on the perforation velocity of the projectile. Back-side damage on medium and high hardness plate is presented in Fig. 1. There is perforation of 20 mm thick steel armour plate due to plugging. At higher hardness, plug thickness is more than that at lower hardness.

4.2 Perforation Velocity & Hardness

The variation of perforation velocity with plate hardness is presented in Fig. 2, wherein a 20 mm diameter, ogive-shaped steel projectile was impacted on 20 mm thick RHA plates of 300, 350, 400, 440, 470 and 520 HV hardness, at zero obliquity. On examination of the back-face of these plates, it was observed that at higher hardness (HV > 400) there was plugging of the plate material in the area of impact. At lower hardness (HV 300 and 350), there was no plugging and the mode of plate failure occurred as ductile-hole growth. It was observed from Fig. 2 that the critical velocity at which plates started getting perforated was decreasing with increasing plate hardness. Thus, the plates with low hardness have better absorption of projectile energy than the plates with higher hardness. The highest hardness plate (HV = 520) exhibited least perforation velocity and the lowest hardness plate exhibited higher perforation velocity. This kind of plate behaviour is contrary to the behaviour noticed in the earlier publication[3]. The reason for such a behaviour of the tempered steel armour plate is explained here.

4.3 Plugging Velocity & Hardness

The plugging velocity is defined as the striking velocity of the projectile at which plate material starts deforming in the form of a plug. Figure 3 provides variation of plugging velocity with the plate hardness. The diameter of the plug and its thickness increased with the plate hardness. Slope of the curve in Fig. 3 is high, thereby indicating the onset of plugging with increasing plate hardness at much lower velocity of the projectile. It is mainly related to the formation of ASBs in the deformed zone of the plate material.

5. DISCUSSION

Plate perforation velocity has been observed to decrease with the increasing plate hardness (Fig. 2). This decreasing trend of the perforation velocity is supported by the data presented in Fig. 3. Therefore, decrease in perforation velocity is associated with decrease in plugging velocity. The reason for decreasing perforation and plugging velocities[3,5] can be explained on the basis of the following equations:

$$\sigma = K\varepsilon^{n}(1-CT) \quad (1)$$

$$\varepsilon_c = [n\rho Cp / vKC \quad (2)$$

Equation (1) represents the constitutive equation for plastic flow and Eqn (2) provides sufficient and necessary condition for the formation of ASB in the plate material under high strain rate deformation process. The value of n was observed to decrease with increasing plate hardness and the value of K was observed to increase with increasing hardness of the plate[3].

In a given plate of a particular hardness the ρ, Cp, v and C are constant, therefore ε_c for ASB formation is directly proportional to n and inversely proportional to K. With increasing plate hardness, decrease in n and increase in K, cummulatively brings down ε_c level and the ASB formation is facilitated (Fig. 4), which is a favourable condition for plugging tendency in the plate material. The formation of a large number of ASBs around the crater in the plate material gives rise to deep cracks in the material, causing the deformation process to take place at lower energy levels. Thus, ultimately the plate perforation velocity is reduced accordingly as shown in Fig. 2. Experimental observations match very well with the theory.

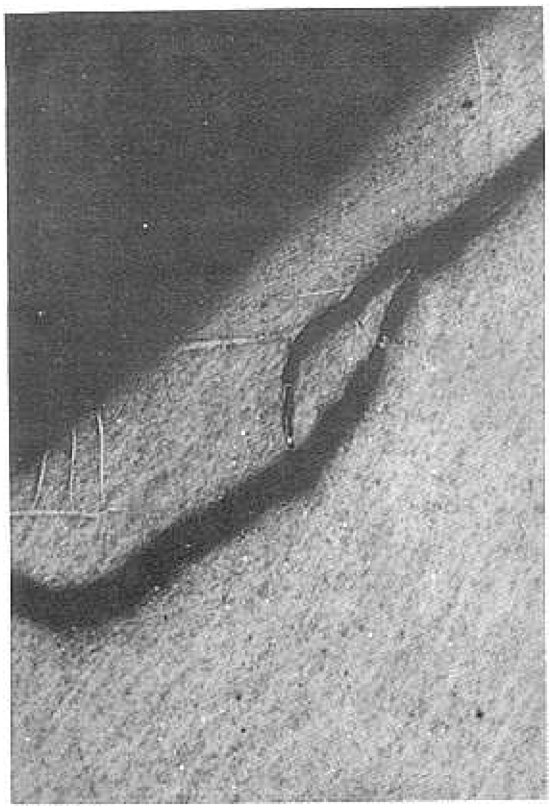

Figure 4. Formation of adiabatic shear bands near the edge of the crater in 20 mm thick steel armour plate at high hardness (520 HV), when impacted by 20 mm diameter steel projectile at normal.

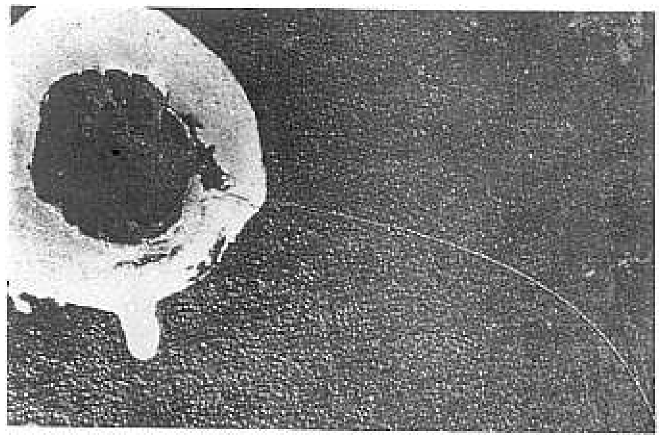

Figure 5. Deep crack formation in 20 mm thick steel armour plate at high hardness (520 HV), when impacted by 20 mm diameter steel projectile at normal.

During the experiments, it was also observed that the high hardness plate (520 HV) developed a deep crack throughout the target plate, even when the plate was not perforated. Such a crack developed in the plate is shown in Fig. 5 and it suggests that there is a likelihood of the shattering/cracking of the armour plate for a particular plate-projectile combination at higher plate hardness. The reason for the initiation and propagation of such cracks is linked with the decreased strain-hardening exponent in the high hardness plates. During the process of joining these high hardness plates by way of welding, the plate cracking is further likely to get enhanced unless special welding techniques are developed.

6. CONCLUSION

With increasing plate hardness, plate perforation velocity is reduced due to decrease in n and increase in K, leading to the formation of a large number of ASBs in the plate material.

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