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# Effect of heat treatment on ballistic performance of an armour steel against long rod projectile

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ABSTRACT

Ballistic performance of an armour steel at different tempering conditions against a tungsten heavy alloy long rod kinetic energy projectile has been investigated. The ballistic performance was found to increase with decreasing tempering temperature but the performance increments were not proportional to the strength increase caused by the tempering. Both target and projectile underwent fragmentation at the penetration interface in all the three targets. Apart from the strength target material deformation behaviour also showed considerable influence on ballistic performance. The ballistic performance appears to increase with decreasing toughness for a given strength.



## 1. Introduction

Penetration of a long rod kinetic energy projectiles in a target have been found to happen in three phases, transient, steady state primary penetration and a non steady state secondary penetration [1]. For projectiles with large L/D ratio, the penetration will predominantly happen by steady state penetration and the contribution from transient and secondary penetration will be very less [2–4]. During steady state penetration, projectile will be consumed simultaneously with target material by erosion, leading to a decrease in the length of the projectile with increasing penetration [5,6]. Steady state penetration has been observed in various experimental studies for different target - projectile combinations [7–14]. Penetration velocity and the projectile consumption rate will be constant during steady state penetration. Towards the end of the penetration for a small length, the projectile erosion will stop and the non steady state penetration will occur by deceleration of the projectile until the projectile lost its kinetic energy. For large L/D ratio projectiles, the total penetration depth can be approximated by assuming complete steady state penetration. By balancing the projectile and target consumption rate the penetration depth (P) can be given by Ref. [15]

$$P = LU/(V - U) \tag{1}$$

where L is the length of the projectile, V is impact velocity of the projectile and U is penetration velocity. The penetration efficiency P/L can be given by,

$$P/L = U/(V - U) \tag{2}$$

The physical meaning of penetration efficiency during steady state penetration is relative consumption rate of the target and projectile material. The efficiency of penetration will be determined by the rate at which the material is removed from the crater (U) and the rate at which the projectile material is utilized (V–U). In fact projectile consumption rate will also be determined by the consumption rate of the target material because the impact velocity V is constant during penetration. The effect of change in penetration velocity on ballistic performance will be twofold. It can be seen from equation (1) that the change will directly affect the depth of penetration because increasing penetration velocity will increase the depth of penetration proportionally. The change in penetration velocity will also affect the consumption rate of the projectile there by the duration of penetration. For instance, the increase in penetration velocity will result in decreasing the consumption rate of the projectile and thereby increasing the duration of penetration which will result in increased depth of penetration.

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**Table 1**
Chemical composition.

| Material | Chemical composition |
|---|---|
| Steel | 0.28–0.33% C, 0.4–0.6% Mn, 0.1–0.25% Si, 1.3–1.5% Cr, 1.5–1.7% Ni, 0.45–0.5% Mo, 0.08–0.12% V, balance Fe |

Target and projectile material behaviour plays a major role in determining the ballistic performance. Apart from strength, material properties like strain hardening, thermal softening, ability to accommodate large deformation considerably influence the penetration efficiency [16–18]. In the present study the effect of target material properties on the ballistic performance against tungsten heavy alloy (WHA) long rod projectile has been studied. Three different mechanical properties were obtained by varying heat treatment cycle in an armour steel. All three target materials were tested against a fixed L/D projectile at a constant impact velocity. This enables us to reason the observed difference in performance with deformation behaviour of the target material.

## 2. Materials and experimental procedure

The steel used in the present study is a medium carbon low alloy steel. The chemical composition of the steel is shown in Table 1. The heat treatment consists of quenching and tempering. Hot rolled steel plates were austenized at 910 °C and oil quenched. Tempering was done at three different temperatures 650 °C, 500 °C and 450 °C in order to attain the expected variation in mechanical properties. The samples were air cooled after tempering. Yield strength, Ultimate tensile strength, elongation, hardness and impact toughness were evaluated for all the three target materials. Ballistic evaluation was carried out using a tungsten heavy alloy projectile with an L/D ratio of 16 at an impact velocity of 1600(1588–1620) m/s. Projectile density and hardness were 17.5 g/cc and 515 HV respectively. The testing was carried out at 0° obliquity. The target plates were stacked in sufficient numbers such that the thickness is sufficiently larger than the depth of penetration in order to give semi infinite thickness. The target plate dimensions with respect to projectile diameter are 1.7D × 17D × 40D. Five tests were carried out on 650 °C and 500 °C tempered targets and three tests were carried out on 450 °C tempered target. After ballistic penetration, target and projectile fragments of each target material were collected and studied using optical and scanning electron microscopy. The projectile fragments collected from the craters are shown in Fig. 1. The cross section of the individual target material craters was also examined to understand the deformation behaviour.

## 3. Results and discussion

### 3.1. Ballistic performance

The mechanical properties of the target materials along with normalized depth of penetration (P/L) are given in Table 2. When decreasing the tempering temperature yield strength and ultimate tensile strength of the steel increases whereas the toughness decreases. The tensile strength of steel plates tempered at 450 °C (SP450) and 500 °C (SP500) is 50% higher than that of the plate tempered at 650 °C (SP650). The mechanical properties are similar in case of SP500 and SP450 except percentage elongation and toughness which shows a significant drop in SP450.

The ballistic performance is shown in terms of normalized depth of penetration in Table 2. SP500 shows only 3% improvement over SP650 even though the difference in tensile strength is 50%. But SP450 with almost similar strength and reduced toughness to that of SP500 shows a 10% improvement in performance over SP650. The ballistic performance shows an increasing trend with increase

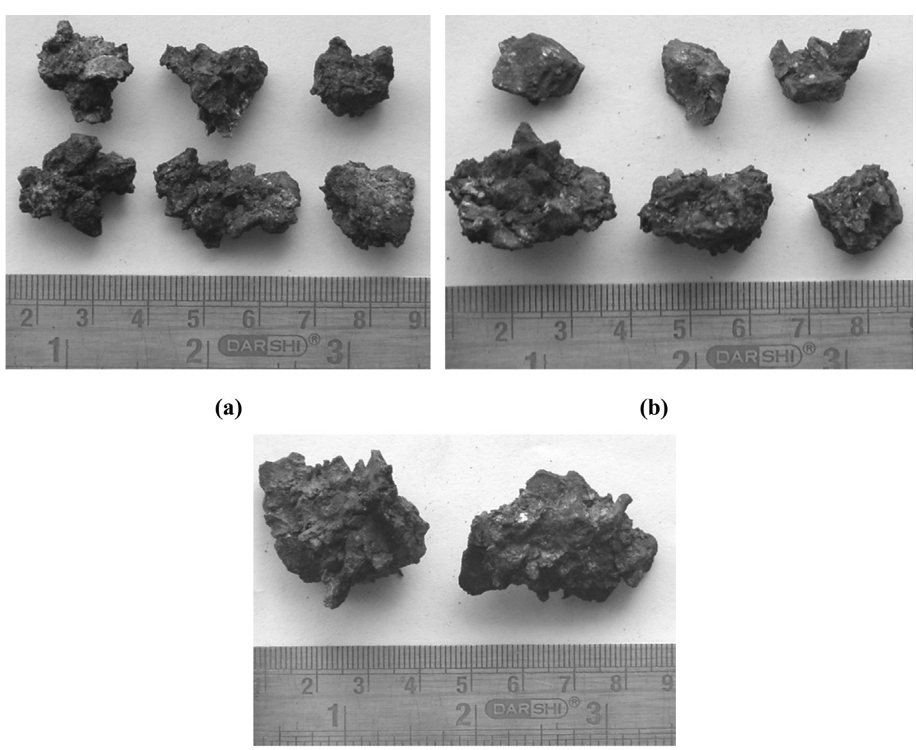


**Fig. 1.** The fragments collected from the target crater (a) SP650, (b) SP500, (c) SP450.