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Effect of tempering time on the ballistic performance of a high strength armour steel

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Abstract

The investigation describes and analyses the effect of tempering time on the mechanical and ballistic performance of a high strength armour steel. The steel is subjected to tempering at 300 °C for 2, 24 and 48 h. A marginal variation in strength and hardness is observed with increase in tempering time, whereas ductility and Charpy impact values are found to be decreasing. Ballistic performance of the samples are evaluated by impacting 7.62 mm and 12.7 mm armour piercing projectiles at 0° angle of impact. Results show a small variation in the ballistic performance when impacted with 7.62 mm armour piercing projectile. A decrease in ballistic performance of the material is observed with increasing tempering time when impacted with 12.7 mm armour piercing ammunition.

Keywords: Ballistic performance; Tempering time; Armour steel; Impact energy

1. Introduction

Suitable material selection is very crucial with respect to reduction in weight of armour and it is essential to determine the material with lowest possible areal density for a defined threat. Many high strength steels, aluminium alloys and titanium alloys are being used as armour. Amongst them high strength steels are predominantly used for armour applications owing to their low cost, superior mechanical properties, good machinability and high performance. Ballistic performance of metallic materials depends on parameters like strength, hardness, toughness, microstructure, strain hardening rate, etc. An optimization of these material properties against projectile impact has long been of practical interest in military applications. Some previous studies showed that ballistic performance largely depends on the hardness of the material.

Dikshit, Kutumbrao, and Sundararajan (1995) found that under plain strain condition the ballistic resistance increases linearly with hardness of the steel. But, under plane stress conditions optimum ballistic performance is observed at an intermediate hardness level. In another study on the ballistic testing of 50CrV4 steel, it was pointed out that with increase in hardness of the target plate the penetration ability of the projectile decreases significantly (Ubeyli, Yildirim, & Ogel, 2007). Maweja and Stumpf (2008a, 2008b) found that the microstructure and the ratio of yield to tensile strength had a significant influence on the ballistic behaviour of armour steels. In a recent study on the ballistic behaviour of different high strength steels by Borvik, Dey, and Clausen (2009), it was demonstrated that there is a linear increase in perforation resistance with yield stress. Srivathsa and Ramakrishnan (1999) formulated ballistic performance maps for thick metallic armour target plates, and indicated that ballistic performance is a strong function of strain-hardening rate. In a previous study it was shown that ballistic performance does not depend on any specific independent parameter. Instead, an optimized value of all the parameters like strength, hardness, toughness leads to the best ballistic performance (Jena et al., 2010).

Heat treatment is the commonly used process to develop desired properties in steels. Of all the microstructures produced by heat treatment, martensite forms the highest level of strength in steels. However, because of large internal stresses

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Table 1
Chemical composition of the steel.

Material	Chemical composition
DMR 1700 steel	0.35–0.44% C, 0.45–055% Mn, 1.8–2.2% Si, 0.8–1.2% Cr, 2.5–3.4% Ni, 0.45–0.55% Mo, 0.25–0.35% Co, 0.01% P, 0.01% S, Balance Fe

associated with the martensitic transformation, martensite phase is rarely used in an untempered condition. Tempering increases the ductility and toughness in steels, which are essential for enhancing impact energy absorption. In tempering two parameters, namely, temperature and time, play vital roles in determining the mechanical properties of the steel. A considerable amount of work has been carried out to understand the effect of tempering temperature on the mechanical properties of steel (Demir, Übeyli, & Yıldırım, 2008; Jena, Ramanjeneyulu, Sivakumar, & Bhat, 2009; Lee & Su, 1999; Malakondaiah, Srinivas, & Rao, 1997). These studies reflect that the temperature employed for tempering is limited because of the loss of strength resulting from the high tempering temperatures. Temper embrittlement is another factor restricting the choice of temperature. Hence it is of interest to explore the effect of tempering time. Only limited studies on the effect of tempering time on the properties of steel are reported in open literature. In one of the earlier works, Lee and Su (1999) found that there is a slight decrease in strength and hardness with increase in tempering time. However, it was observed that ductility increases with increase in tempering time.

2. Material and experimental procedure

DMR-1700 steel is a medium carbon high strength armour steel. Previous studies on this steel showed that 300 °C tempering temperature gives maximum strength (Malakondaiah et al., 1997). But the Charpy impact values obtained at this tempering temperature are not high. The low Charpy impact values are the contributions of the residual stresses at 300 °C tempering temperature. Charpy impact toughness is an important parameter which contributes to the ballistic performance (Jena et al., 2010). So it is aimed in this study to explore the effect of increased tempering time on mechanical properties including Charpy impact values and ballistic performance of DMR-1700 steel.

The steel was made by vacuum arc melting in Mishra Dhatu Nigam Limited, India. It was supplied in the form of 50 mm thick rolled plates. The nominal chemical composition of the steel is given in Table 1. Samples of 150 mm × 150 mm × 50 mm were cut from a single plate and subjected to heat treatment. For the present tests, the austenitisation temperature was 925 °C and the tempering temperature was 300 °C. The samples were first austenitised for 2 h followed by quenching in oil. The plates were immediately tempered for 2 h, 24 h and 48 h followed by cooling to room temperature in air. Austenitizing and tempering were carried out in a neutral atmosphere furnace.

Small samples were cut from the heat-treated plates and subjected to standard metallographic examination. The specimens were etched at room temperature using 2% Nital (2 ml HNO_3, and 98 ml Methyl Alcohol) to reveal the microstructure. Optical and scanning electron microscope (SEM) was used to observe the microstructure of the heat-treated plates. Following metallographic observations, the bulk hardness of the target plates were measured according to ASTM E 140-02 using an AFFRI Vickers hardness tester under 30 kg applied load for 15 s. The average hardness of a particular sample was reported from measurements over 10 locations.

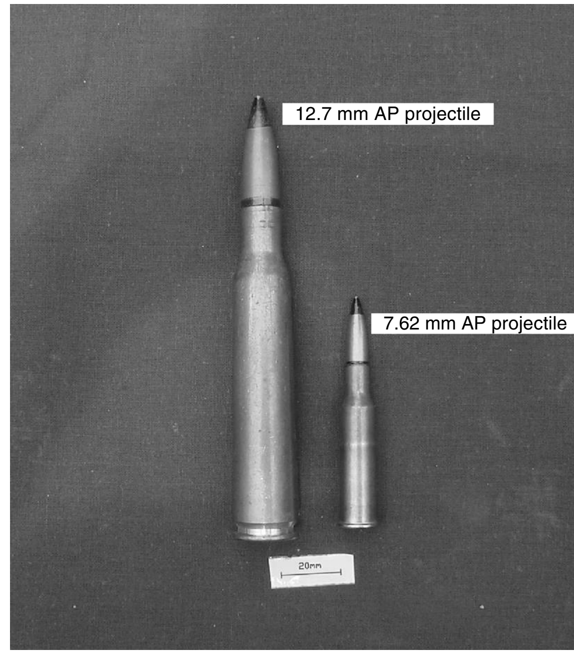

Fig. 1. Photographs of the two different armour piercing projectiles used for the present study.

Cylindrical tensile specimens were machined from the heat treated plates in the longitudinal orientation of the rolled plate. The size and geometry of the specimens as well as the testing procedure are in accordance with ASTM E8-93. Tests were done at a strain rate of $4.8 \times 10^{-1}\ s^{-1}$ using an Instron Universal Testing machine (Instron 5500R) to determine the mechanical properties. Three samples for each heat treated condition were prepared and tested at room temperature. Standard Charpy V-notch (2 mm deep notch) specimens (10 mm × 10 mm × 55 mm size) were also machined as per the ASTM standards (E23-02a) and the tests were carried out using the Tinius-Olsen impact testing instrument to find out the impact properties. The weight of the hammer used in the impact test was 27.3 kg. Five samples of each heat treatment were tested and the average value was taken as the impact value of plates for that heat treatment. Following the Charpy impact testing, the fracture surfaces of broken impact specimen were also carried out. The topographical features were observed by using a LEO scanning electron microscope operated at 20 kV.

Heat treated steel plates were impacted with 2 different non-deformable armour piercing steel projectiles. Fig. 1 presents the general views of the projectiles. Table 2 gives more detailed description of the projectiles. The angle of attack was normal to the target plates. The striking velocity of the projectiles was measured using infrared light emitting diode photovoltaic cell