Materials Science and Engineering A 485 (2008) 140–153

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

The design of advanced performance high strength low-carbon martensitic armour steels Part 1. Mechanical property considerations

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Received 13 February 2007; received in revised form 23 July 2007; accepted 15 August 2007

Abstract

In a series of experimentally tempered martensitic steel alloys it was observed that for a given chemical composition, the heat treatment parameters for advanced ballistic performance are different from those required for higher mechanical properties, rendering the often specified relationship between mechanical properties and ballistic performance questionable. Systematic analysis of the microstructures and the fracture surfaces of 13 laboratory melted tempered martensitic armour plate steels was carried out to understand the improved ballistic performance of these steels of which the mechanical properties were actually lower than currently specified for military and security applications. It was, furthermore, observed that the detrimental effect of inclusions on ballistic performance depends on the tempering temperature and on the strain rate.

Keywords: Armour steel; Mechanical properties; Ballistic performance; Strain rate; Martensite; Inclusions

1. Introduction

Some recent authors have pointed out the lack of correspondence between mechanical properties and ballistic performance of armour plate materials, rendering the hitherto used strength and hardness-based design specifications questionable [1–6]. An alternative microstructural approach to the prediction of the ballistic performance of armour steels has, therefore, become necessary. The microstructural response to ballistic impact of martensitic steel plates with thicknesses less than 6.0 mm was presented in our previous work [7].

In this work a comparison of the effect of manganese sulphide inclusions in "slower" strain rate Charpy impact tests at −40 °C and tensile tests at room temperature, and in "higher" strain rate ballistic tests on the fracture mode of plates was made to explain the discrepancies between the performance predictions based on mechanical properties as in many current design specifications, and the observed ballistic performance for plates of tempered martensitic steels with thicknesses less than 8.5 mm.

Localised thin foil TEM of ballistic impacted regions of these steels suggested the presence of high temperatures during the impact that induced phase transformations from an initial twinned martensite to austenite and back to an untwinned martensite [7]. This observation agreed with the proposals by Bai and Dodd [8], and by Rosenberg and Dekel [9] of the existence of adiabatic shear bands formed in the regions of the impact inside which temperatures higher than 720 °C may be reached, inducing the phase transformation.

Penetration of metallic armour by a high-speed projectile has been a subject of considerable research interest. It suits to note that to this day there is no norm or universal standard for the design of armour steels. Each country or group of countries adopts testing range specifications and procedures dictated by their own defined objectives and threat levels (i.e. plate thickness, type and weight of ammunition, minimum and maximum velocities, number of impacts, assessment criteria of a successful test). The manufacturers are often obliged to align their product properties with the changeable needs of the various customers. The most commonly used and most comprehensive test standards are those published by the United States National Institute

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0921-5093/$ – see front matter
doi:10.1016/j.msea.2007.08.048

of Justice (NIJ). These were developed to provide armed forces with a uniform standard against which body armour is to be tested. Other organisations now use these standards for their own purposes. The North Atlantic Treaty Organization (NATO) has developed its own standards which are commonly known by the acronym STANAG. Australia and New Zeeland have developed standards as well, which are referred to as AS/NZS. The United Kingdom Police Science Development Branch (PSDB) researched stab attacks and developed a standard and test regime which are now used worldwide and have been adopted as part of the NIJ Standards. South Africa has introduced new ballistic testing specifications and assessment criteria for integrated armour components to meet specific needs in the threat against law enforcement. It is, therefore, not unusual for users to develop a specific test requirement for a material based on its intended use.

Most of these standards consider the ballistic limit as a critical parameter used in the vulnerability assessment of targeted systems. Probabilistic in nature, all definitions refer to the threshold velocity V_{50} dividing penetrating and non-penetrating events. Czarnecki considered the V_{50} parameter as the small range of velocities over which all the projectile's kinetic energy is transferred to the target [10]. The V_{50} is a function of many parameters associated with the impact event. The variables include projectile parameters (i.e. nose shape, cross-sectional area, *L–D* ratio, mass and rigidity) and target parameters (i.e. material properties, thickness, lay-up and boundary conditions) among others [10]. Naik et al. identified and defined 45 parameters and functions to model the ballistic impact behaviour of woven fabric composites [11]. For simplicity, the V_{50} is customarily determined only for shotlines normal to the target's surface. When a more precise definition of the ballistic limit is desired, one is forced to perform several impact experiments in order to converge to the V_{50}.

STANAG pre-specifies the ballistic limit velocities V_{50} = 580, 980, 1536 and 2008 m/s corresponding to NATO 7.62 mm armour piercing (AP) for a maximum thickness possible of t = 80 mm. NIJ pre-specifies V_{50} = 400, 600 and 800 m/s corresponding to the US Ball M33 0.5. Each standard should represent the most severe common threat.

Ballistic performance is known to correlate with dynamic deformation behaviour as well as the formation of adiabatic shear bands [12]. Hickey proposed another method to evaluate the ballistic performance by the mass efficiency, E_m, which is the weight ratio against the rolled homogeneous armour (RHA) having identical ballistic properties as shown below [13]:

$$E_m = \frac{(\text{weight/area})\text{ of RHA}}{(\text{weight/area})\text{ of Ti–6Al–4V}} \text{ at the same } V_{50} = \frac{(\text{density} \times \text{plate thickness})\text{ of RHA}}{(\text{density} \times \text{plate thickness})\text{ of Ti–6Al–4V}} \text{ at the same } V_{50}$$

It is inferred from the work by Lee et al. that the mass efficiency varies by 2–9% when the V_{50} varies by only 1% [14]. Lee et al. conducted tensile tests at room temperature at a strain rate of $10^{-3}\ s^{-1}$, using quasi-static and dynamic torsional tests by the Kolsky bar technique [14] to establish a correlation between microstructure, ballistic performance and adiabatic shear banding behaviour [14]. They have shown that the V_{50} can be improved by optimising the microstructure in the same material with the same thickness or aerial density. This is also the approach adopted in this work as also suggested by Hammond and Proud [6], Bai and Dodd [8], Rosenberg and Dekel [9] and others.

Some studies have shown that the two- or three-dimensional state of stresses and strains, depending on the thickness of the armour plate, can drastically affect the contributions of the geometry and hardness of the target on its ballistic performance [15,16].

Ben-Dor et al. [17] developed a dimensionless analytical expression for the optimum design of two-component armours, which is applicable to arbitrary material combinations. In their design criterion, the ballistic limit velocity is prespecified, and the minimal aerial density is taken as the optimum objective.

Many semi-empirical and analytical models are currently under development to enable the prediction of ballistic performance. Most of them consider mechanical properties at room temperature at low strain rates as well as the strength and elongation properties at higher strain rates determined by using the Split Hopkinson Pressure Bar as input [3,4,10,16,17,20,21,26].

The effect of the armour material's non-homogeneities, the shape and distribution of inclusions and precipitates, the grain boundaries geometry and the initial phases present do not appear explicitly in these models. The changes in the behaviour of these material constituents at ballistic strain rates can be one of the explanations for many of the different observations by previous authors [6,8,9].

2. Materials and experiments

2.1. Chemical composition and manufacturing

Initially five experimental armour steels, namely steels G1A through to G3 were subjected to standard ballistic testing described in Section 2.2 [19] and their performance compared to those of three currently produced and used armour steels, here named A66, M38 and RL5. Their chemical compositions are shown in Table 1.

The 5 kg vacuum melted alloys were cast into a 45 mm × 70 mm × 230 mm mild steel mould, the ingots were solution treated for 1 h at 1100 °C before hot rolling in four passes of 20% reduction each down to 6 ± 0.2 mm thickness at a finishing temperature of between 950 and 900 °C and then air cooled. The plates were then austenitised at 900 °C for 20 min, water quenched and tempered at 180 and 250 °C for 20 min and 1 h. The microstructures and the phases present before ballistic testing were analysed by thin foil transmission electron microscopy and X-ray diffraction. The plate's sizes for ballistic testing were 200–250 mm wide and 500–550 mm in length.