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Effect of Hardness on the Ballistic Impact Behavior of High-Strength Steels Against 7.62-mm Armor Piercing Projectiles

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Ballistic performance of engineering materials should be known in selection of the most suitable armor material to protect civilian or military system with the lowest possible weight against various threats. In this study, the ballistic impact characterization of high-strength steels, namely AISI 4340 and DIN 100Cr6, was investigated using 7.62-mm armor piercing (AP) projectiles by considering four hardness levels and five areal densities. The main aim was to examine the effect of hardness and areal density on the ballistic behavior of these steels. Hence, four different heat-treatment schedules were applied to these steels to get different mechanical properties. After ballistic testing, macro and micro examinations of the specimens were carried out to clarify their failure mechanisms. According to the results, the AISI 4340 steel having a hardness of ~50 HRC showed the best ballistic performance among the investigated materials.

Keywords ballistic testing, heat treatment, high-strength steel

1. Introduction

Saving weight in the armor system for defense applications is strongly needed to increase the mobility of the system and to decrease the energy consumption. Hence, the use of armor material with the lowest possible areal density resisting ballistic threats is very important in decreasing the weight of a system. Steel has been widely used in armor applications for a long time due to its superior mechanical properties, very large technological database, relatively cheapness and easy formability. Even though it has a disadvantage of high density, this can be tolerated by increasing hardness and strength with suitable heat treatment to achieve an armor system having a lower areal density.

In an earlier study, Manganello and Abbott (Ref 1) examined the effect of steel properties on the low velocity impact behavior of steel armors. They found that the hardness was the most critical parameter affecting the ballistic performance of the steels (Ref 1). In another earlier study (Ref 2), conducted on metallic armor systems, a comparison criterion was suggested for metallic armor selection by considering the physical-mechanical properties and the cost of the candidate materials. This work concluded that titanium alloys and Hadfield steel showed better ballistic performance than the aluminum alloys and non-Hadfield steels (Ref 2). In addition, high-velocity ballistic testing of the rolled homogeneous armor (RHA) steel targets was conducted using two-stage gas guns at striking velocities of 1.5-4 km/s to clarify the penetration mechanics in the hypervelocity range (Ref 3). Moreover, the normal and oblique impacts of a 6.2-mm projectile for the mild steel were studied by Gupta and Madhu (Ref 4). They showed that the difference between the angles of obliquity for the ballistic limit and the critical ricochet increased with the increase in the plate thickness (Ref 4). Furthermore, Dikshit et al. (Ref 5) investigated the effect of plate hardness on the ballistic behavior of steel plates over the velocity range of 300-800 m/s. They found that the effect of hardness of a plate on the ballistic performance varied depending on the stress state (Ref 5).

In a different work, ballistic performance of the single and multilayered plates of mild steel, RHA, and aluminum was carried out against the 6.2-mm projectiles with a velocity range of 800-880 m/s (Ref 6). It was concluded that when the number of layers was more than two, the ballistic resistance of these materials decreased. On the other hand, the ballistic performance of nitrogen alloyed austenitic steels and high-strength armor steel was evaluated using a light gas gun at a projectile velocity of 2500 m/s (Ref 7). Both steels showed similar ballistic performances (Ref 7).

In a study by Reddy et al. (Ref 8), the ballistic performance of high-strength low-alloy steel weldments against 7.62-mm projectiles was investigated. The shield metal arc weld showed higher ballistic performance compared to either the gas tungsten arc weld or the flux cored arc weld (Ref 8).

Anderson et al. (Ref 9) studied the effect of projectile core hardness on the ballistic resistance of steels. They concluded that ballistic limit velocity was independent on the hardness of projectile core until the hardness of the core was greater than the target hardness.

The ballistic behavior of welded and unwelded tool steels (with 0.95% C) was studied by using the 7.62-mm ball and armor piercing (AP) projectiles (Ref 10). It was pointed out that

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gross cracks occurred at a plate hardness of 510 HV (Ref 10). Dey et al. (Ref 11) studied the effect of target strength on the perforation of structural steels, i.e., Weldox 460 E, Weldox 700 E, and Weldox 900 E, using a gas gun within the velocity range of 150-350 m/s. They found that the ballistic limit velocity decreased for increasing strength of the materials with blunt projectiles, whereas the opposite trend was observed with conical and ogival projectiles. Furthermore, monolithic and layered targets of Weldox 700 E were investigated using a gas gun at sub-ordinance velocity (Ref 12). Borvik et al. (Ref 13) made both numerical and experimental studies on the ballistic impact of Weldox 460 E steel. They found a good agreement between these two studies.

Recently, the ballistic testing of the high-strength low-alloy (HSLA) 50CrV4 steel, against 7.62-mm AP projectiles, was carried out (Ref 14). It was shown that when the hardness of the steel plates was increased, the penetration and propagation ability of the projectile decreased significantly (Ref 14). In addition, Maweja and Stumpf (Ref 15-17) tested different grades of armor steels against the 5.56-mm rounds to see the fracture mechanism and phase transformation in both the impacted and radial zones of these steels. They concluded that the microstructure of the steel had a definite influence on its ballistic performance.

In this study, the effect of hardness and areal density on the ballistic behavior of AISI 4340 and DIN 100Cr6 under the impact of 7.62-mm AP projectiles was studied. The main aim of this research was to investigate the change in the ballistic performances of these steels with respect to their hardness and areal density. Furthermore, 1050 plain carbon steel was also used for comparison. Finally, the failure mechanisms were investigated by visual and scanning electron microscope (SEM) examinations.

2. Experimental Procedure

Steel specimens used in this study were supplied from the market. Specimens were prepared to get five different thicknesses: 7.2, 9.0, 10.8, 12.7 and 14.4 mm, corresponding to the areal density values of 55, 70, 85, 100 and 115 kg/m^2, respectively. A coding system was used to define the nine specimen groups.

0A1

- **Type of material: 0** = AISI 1050, **1** = AISI 4340, **2** = DIN 100Cr6
- **Hardness level (for AISI 4340 and DIN 100Cr6):**
  A = Heat treatment 1, **B** = Heat treatment 2,
  C = Heat treatment 3, **D** = Heat treatment 4.
- **Areal Density (in kg/m^2): 1** = 55, **2** = 70, **3** = 85, **4** = 100, **5** = 115.

After the preparation of the specimens into suitable sizes, alloys AISI 4340 and DIN 100Cr6 were subjected to four different heat treatments. Table 1 presents the heat-treatment procedures for these materials. As a first step, the steels AISI 4340 and DIN 100Cr6 were austenitized at 860 and 880 °C, respectively, for 90 min. Then, they were quenched into water to develop the martensitic microstructure. After that, the steels were tempered at four different temperatures in a salt bath for 2 h to develop four different hardness levels. On the other hand, the 1050 steel was used in as-received condition. After heat treatments, the strength and hardness of the specimens were determined using standard mechanical tests (Ref 18, 19). And

Table 1 Heat-treatment procedure for AISI 4340 and DIN 100Cr6

Steel	Heat treatment no.	Austenitizing temperature, °C	Austenitizing time, min	Tempering temperature, °C	Tempering time, min
AISI 4340	1	860	90	580	120
	2			450	
	3			400	
	4			250	
DIN 100Cr6	1	880	90	550	120
	2			400	
	3			350	
	4			200	

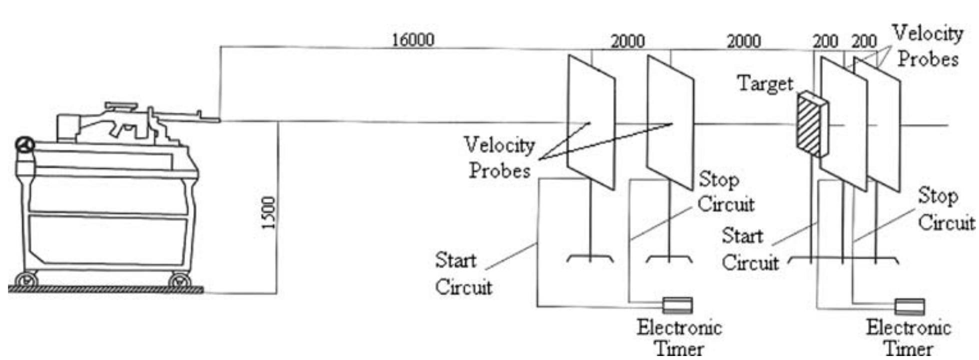

Fig. 1 Experimental setup for ballistic impact testing

also, the microstructural characterization of the specimens was performed using SEM prior to ballistic testing. For the ballistic testing, an experimental setup for target materials was prepared as shown in Fig. 1. The ballistic testing of the specimens was made under the normal impact of 7.62 × 51 mm M61 type AP projectiles. The specimens were fixed in a target located 20 m away from the projectile exit zone. Five separate specimens corresponding to five different areal densities were tested for each specimen type. Tests were repeated five times and the target was subjected to a single shot for every specimen. Hence, 225 separate specimens test were conducted using AP projectiles. The average velocity of the projectiles was recorded as 779 ± 4.5 m/s. Finally, macro and micro examinations of tested specimens were made to reveal their failure mechanisms.

3. Results and Discussion

3.1 Microstructures

Typical SEM microstructures of the tempered 4340 steels are shown in Fig. 2. Tempered martensite (cementite plates in the ferrite matrix) was seen for the AISI 4340 samples.

3.2 Mechanical Properties

Strength and hardness values of the investigated steels are given in Table 2. One can see that the yield and tensile strengths of the AISI 4340 vary in the ranges of 1200-1550 MPa and 1550-1855 MPa, respectively, depending on the heat-treatment conditions. Moreover, the hardness for the steel AISI 4340 changes between 38 and 60 HRC. On the other hand, the 100Cr6 specimens also reached high-strength levels similar to the AISI 4340 specimens. However, the AISI 4340 had higher ductility in terms of (%) elongation than type DIN 100Cr6. The steel AISI 1050 had the lowest strength and hardness among the specimen groups.

3.3 Ballistic Impact Experiments

In ballistic protection, the threat must be stopped by armor material to maintain safety. The propagation ability of the projectiles in an armor material is strongly related to the mechanical properties of the armor. Although the increasing hardness levels of metallic armor reduce the projectile advancement and perforation capability, toughness of the armor is also required to prevent catastrophic failure caused by gross crack formation. In this study, the ballistic impact success of the investigated materials was determined by taking into account the probability of perforation of these materials. Experimental results consisting of the ballistic protection ability of the alloys are given in Table 3. AISI 1050, having the lowest hardness and strength, exhibited the lowest ballistic resistance. The samples of 0A group were completely penetrated and perforated for all areal densities. Figure 3 illustrates the photos of this group after the ballistic impact testing. One can see that the samples failed via hole formation under the impact of the projectile. In other words, the projectile easily penetrated and perforated the samples by creating a ductile hole.

On the other hand, the effect of hardness on the ballistic impact character of the AISI 4340 was significant. Even though the specimen 1A requires an areal density of 115 kg/m^2 to maintain ballistic protection, further increase in the hardness of this steel allowed lower areal densities of the steel capable of stopping the projectile. The best ballistic performance was observed in the 1B specimen group of the AISI 4340. This group satisfied the ballistic protection with the areal density ≥ 70 kg/m^2. Figure 4 depicts the view of the 1B specimens after testing. It can be seen that the projectile did not penetrate the specimens 1B2, 1B3, 1B4, and 1B5. In addition, the target steel was eroded and fractured at the impact surface of these specimens. However, in the samples of 1B2, 1B3, and 1B4 some tensile radial cracking occurred at the exit side.

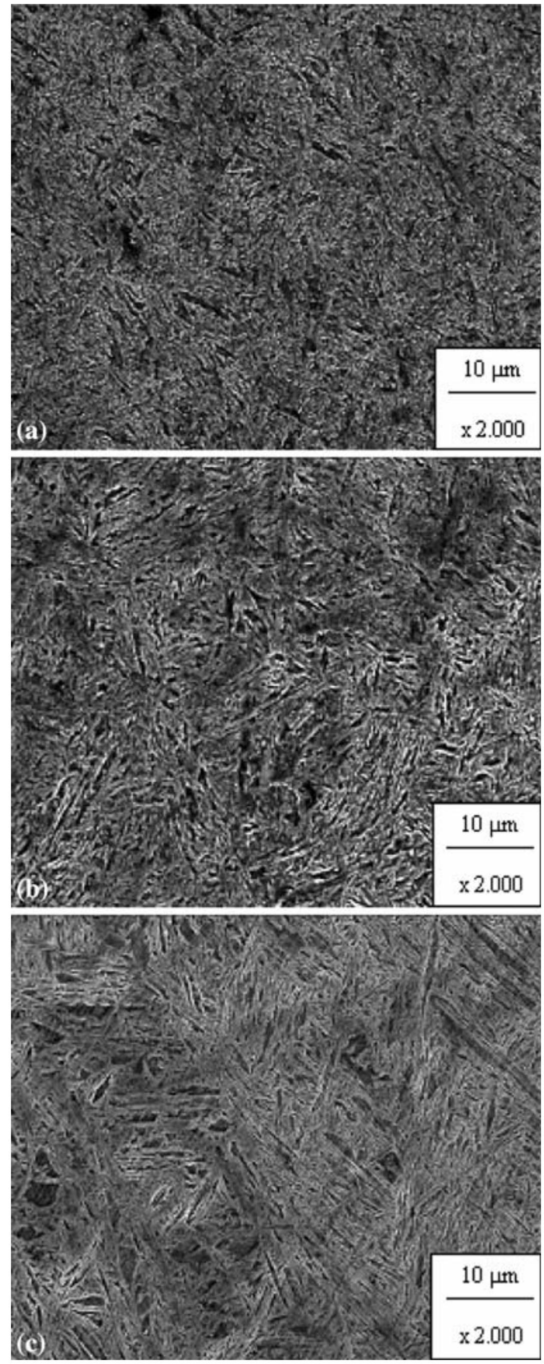

Fig. 2 Microstructure of the AISI 4340 heat treated to (a) 40 HRC, (b) 50 HRC, and (c) 59 HRC by SEM. The samples were etched by 5% nital for 15 s

Table 2 Some important mechanical properties of the investigated materials

Specimen group	Hardness, HRC	Standard deviation for hardness	Yield strength, MPa	Tensile strength, MPa	Ductility % elongation
0A	27.5	1.2	650	900	15.0
1A	39.5	1.5	1200	1550	13.7
1B	49.5	1.9	1300	1600	13.0
1C	52.5	1.6	1400	1775	12.1
1D	58.5	1.6	1550	1855	12.0
2A	40.4	1.6	1200	1570	12.3
2B	48.8	2.0	1300	1650	8.7
2C	57.0	2.0	1450	1800	6.0
2D	59.5	1.3	1600	1950	5.1

Table 3 Probability of the non-perforation of the alloys out of five shots against 7.62-mm AP projectiles

Specimen group	Areal density, kg/m^2				
	55	70	85	100	115
0A	0	0	0	0	0
1A	0	0	0	60	100
1B	0	100 (a)	100 (a)	100 (a)	100
1C	0	0	100	100	100
1D	0	20	100	100	100
2A	0	0	0	100 (a)	100 (a)
2B	0	0	0	0	0
2C	0	0	0	0	20
2D	0	0	0	0	60

(a) Specimen was successful but rear surface had some crack(s)

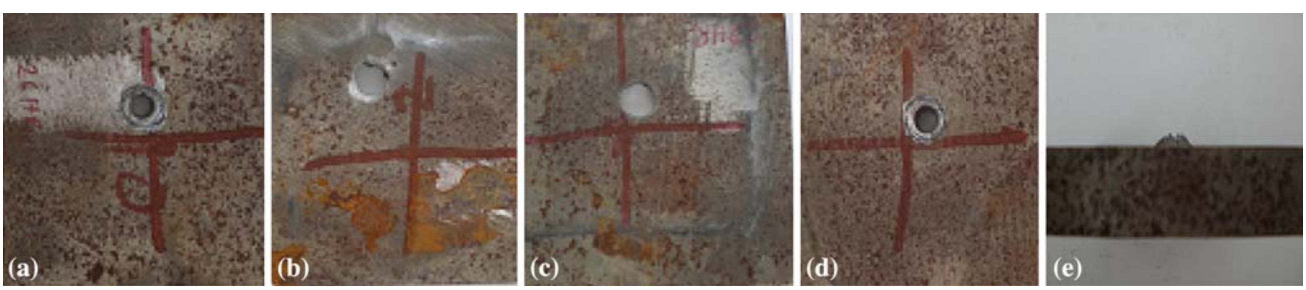

Fig. 3 Macro-view of 0A having areal density of (a) 55 kg/m^2, (b) 70 kg/m^2, (c) 85 kg/m^2, (d) 100 kg/m^2, and (e) 115 kg/m^2 after the ballistic testing

Furthermore, the specimen groups 1C and 1D having an areal density ≥ 85 kg/m^2 were satisfactory against 7.62-mm AP projectiles. Figure 5 and 6 represents the macro photos of the specimen 1C and 1D, respectively. It can be observed that the ballistic performances of these specimens were very similar. In the failed specimens of 1C and 1D, major tensile radial cracks causing failures were seen clearly.

It is interesting to point out that the ballistic resistance of the alloy DIN 100Cr6 was found to be much lower compared to AISI 4340, although the hardness and strength levels were comparable for the two steels. Among the specimen groups of the alloy DIN 100Cr6, only the 2A with an areal density ≥100 kg/m^2 was successful in stopping the AP projectiles. Figure 7 shows the view of the specimens belonging to the group 2A after testing. One can observe that samples 2A4 and 2A5 stopped the projectile but there was one long crack at the exit side of both two samples. The other DIN 100Cr6 targets for all the areal densities under consideration did not show efficient resistance to the AP projectiles. This was directly related to the much lower ductility and toughness of DIN 100Cr6 steel compared to those of AISI 4340, since the plastic deformation taking place at the target material is very effective in absorbing the energy during the projectile impact (Ref 1, 20, 21).

The main reason for the failure of target material under ballistic impact is tensile waves reflected from the rear edge of it. Upon impact of the projectile, compressive stresses occur at the front side of the specimen and these stresses reflect from its rear side as tensile stress waves which cause crack initiation, crack propagation, and finally failure. Figure 8 and 9 shows the photographs of the tested specimens 1C2 and 2C3, respectively.

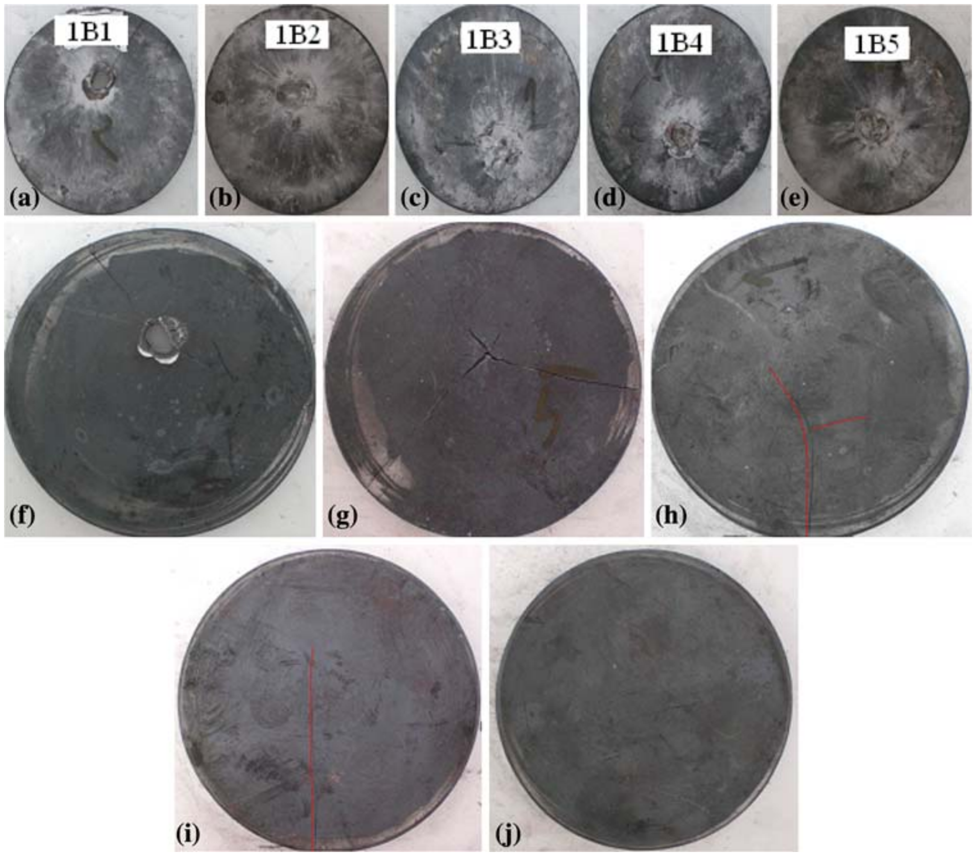

Fig. 4 Front view (a-e) and rear view (f-j) of the specimen group 1B with areal density of 55, 70, 85, 100, and 115 kg/m^2, respectively, after the ballistic impact

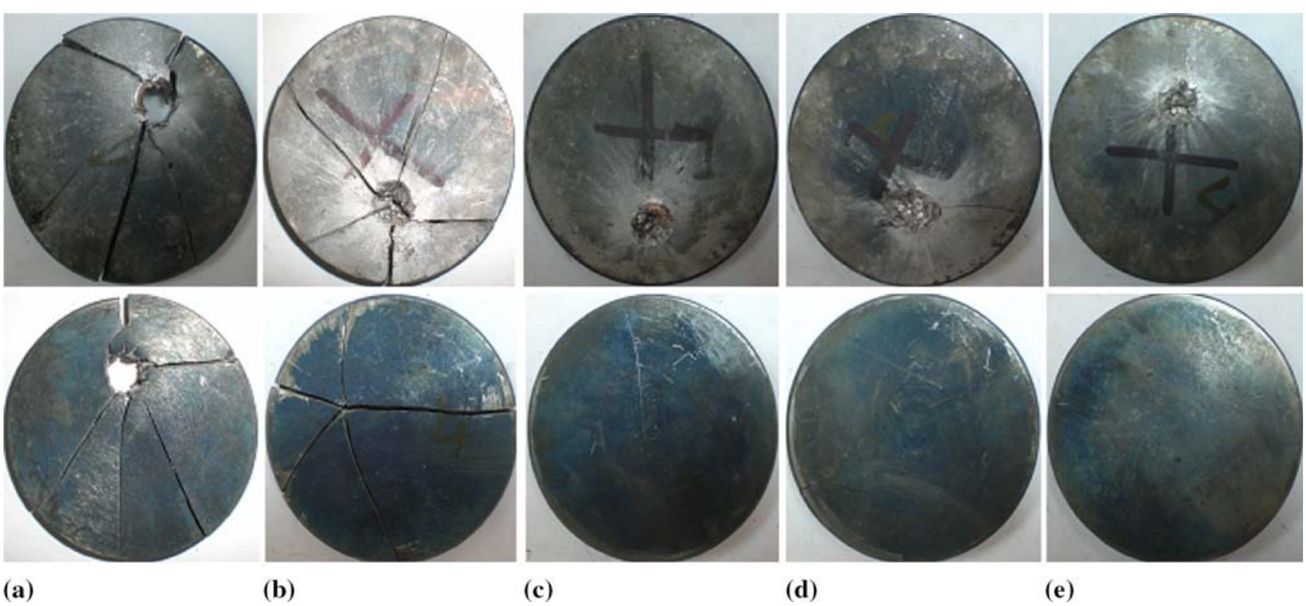

Fig. 5 Front (top) and rear (bottom) photos of the specimen group 1C with areal density of (a) 55 kg/m^2, (b) 70 kg/m^2, (c) 85 kg/m^2, (d) 100 kg/m^2, and (e) 115 kg/m^2, respectively

Shear bands, caused by the reflected tensile stresses, are seen curved or parallel lines to the impacted surface. These bands reveal that the ballistic impact induces cyclic loading in the plates due to multiple reflections of tensile waves (Ref 15). It can be envisioned that the major part of the failure resulted from these tensile stresses. In the failed samples of both AISI

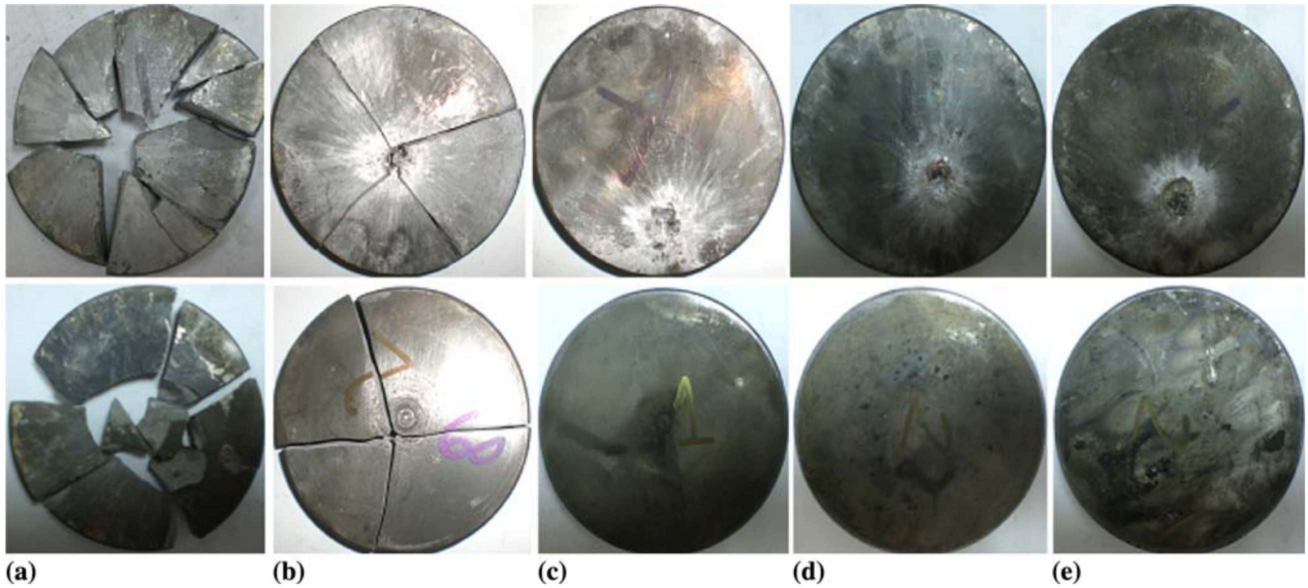

Fig. 6 Front (top) and rear (bottom) photos of the specimen group 1D with areal density of (a) 55 kg/m^2, (b) 70 kg/m^2, (c) 85 kg/m^2, (d) 100 kg/m^2, and (e) 115 kg/m^2, respectively

Fig. 7 Rear view of the specimen group 2A: (a) 2A1, (b) 2A2, (c) 2A3, (d) 2A4, and (e) 2A5. It is apparent that the specimens 2A4 and 2A5 were not perforated by the projectiles but only a radial crack was formed at the rear side of the specimens

4340 and DIN 100Cr6, fine dimples were observed in the zones near the edge of the impacted surface. However, adjacent to the projectile impact region, ductile-like fracture was normally seen for the failed AISI 4340 samples, whereas both intergranular and transgranular fractures (brittle type) were recorded for the failed DIN 100Cr6 samples of 2B, 2C, and 2D.

Experimental results brought out that increasing the hardness from ~40 to 50 HRC improved the ballistic performance of the steel AISI 4340. However, further increase in the hardness did not provide extra benefit with respect to ballistic resistance. For the samples of AISI 4340 with the hardness levels of 53 and 60 HRC, the ballistic performance was found to be somewhat lower than those for samples having a hardness of 50 HRC. On the other hand, increasing the hardness of the steel DIN 100Cr6 decreased both its ductility and ballistic performance significantly. Hence, the steel with hardness ≥50 HRC failed by breaking into several pieces under the impact of AP projectiles. These results pointed out that

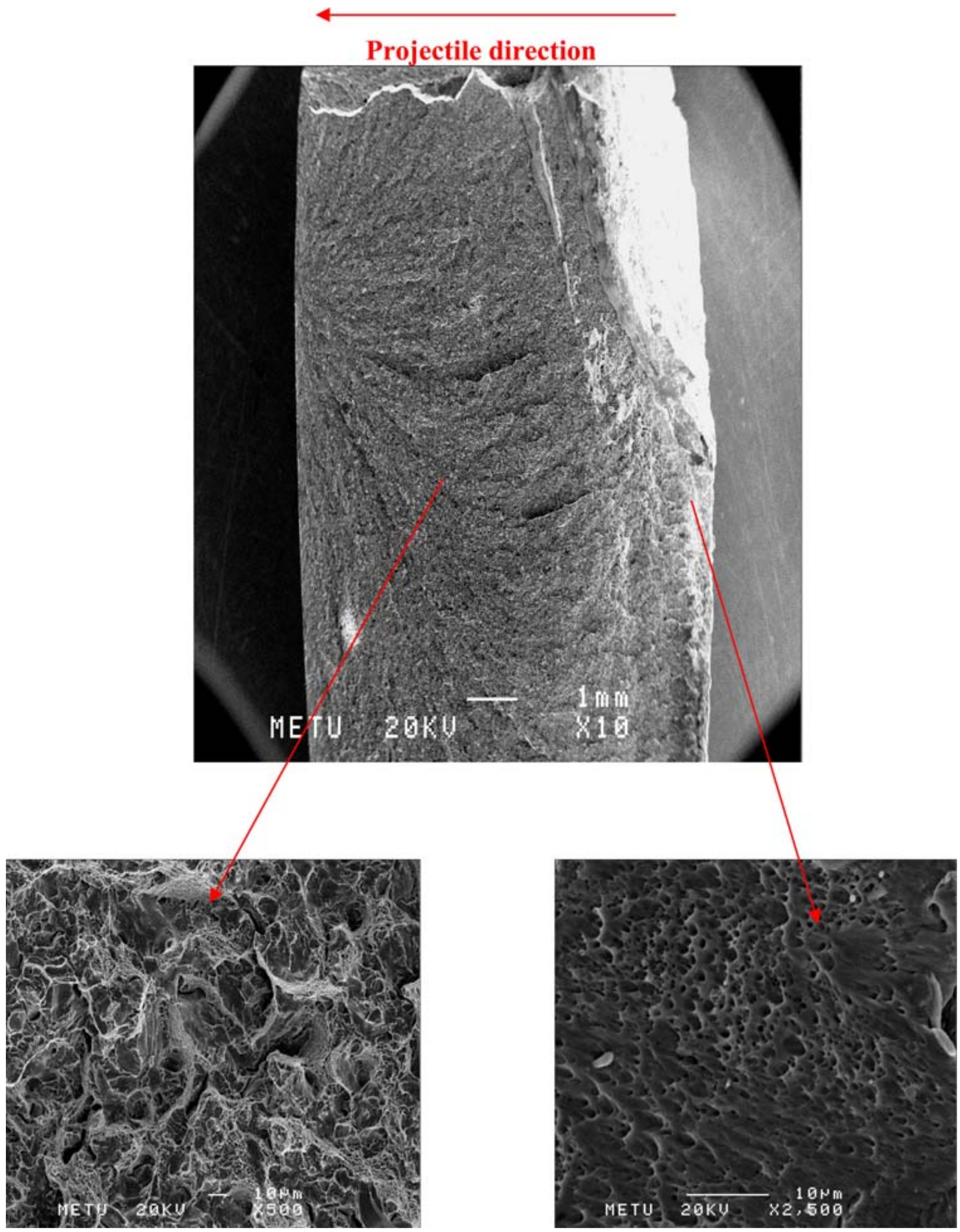

Fig. 8 Views of the surface of the broken specimen 1C2 by SEM

hardness was not the only parameter determining the ballistic performance of the high-strength steels. In order to withstand high reflected tensile waves satisfactorily, the steel should have moderate-to-high ductility and toughness as well as high hardness.

4. Conclusion

According to the experimental results, the main conclusions can be given as follows:

- Among the investigated materials, the highest ballistic resistance was for AISI 4340 which had a hardness of ~50 HRC.
- The ballistic performance of DIN 100Cr6 steel was found to be much less than that of the AISI 4340 steel.
- Ballistic resistance of the tempered martensitic steels is not only dependent on hardness. In other words, knowledge of hardness for these steels is not sufficient to determine, or even estimate, their ballistic behavior.
- AISI 4340 steel could maintain at least 39 and 29% weight saving in comparison to the RHA and high hardness armor steels (Ref 22), respectively.

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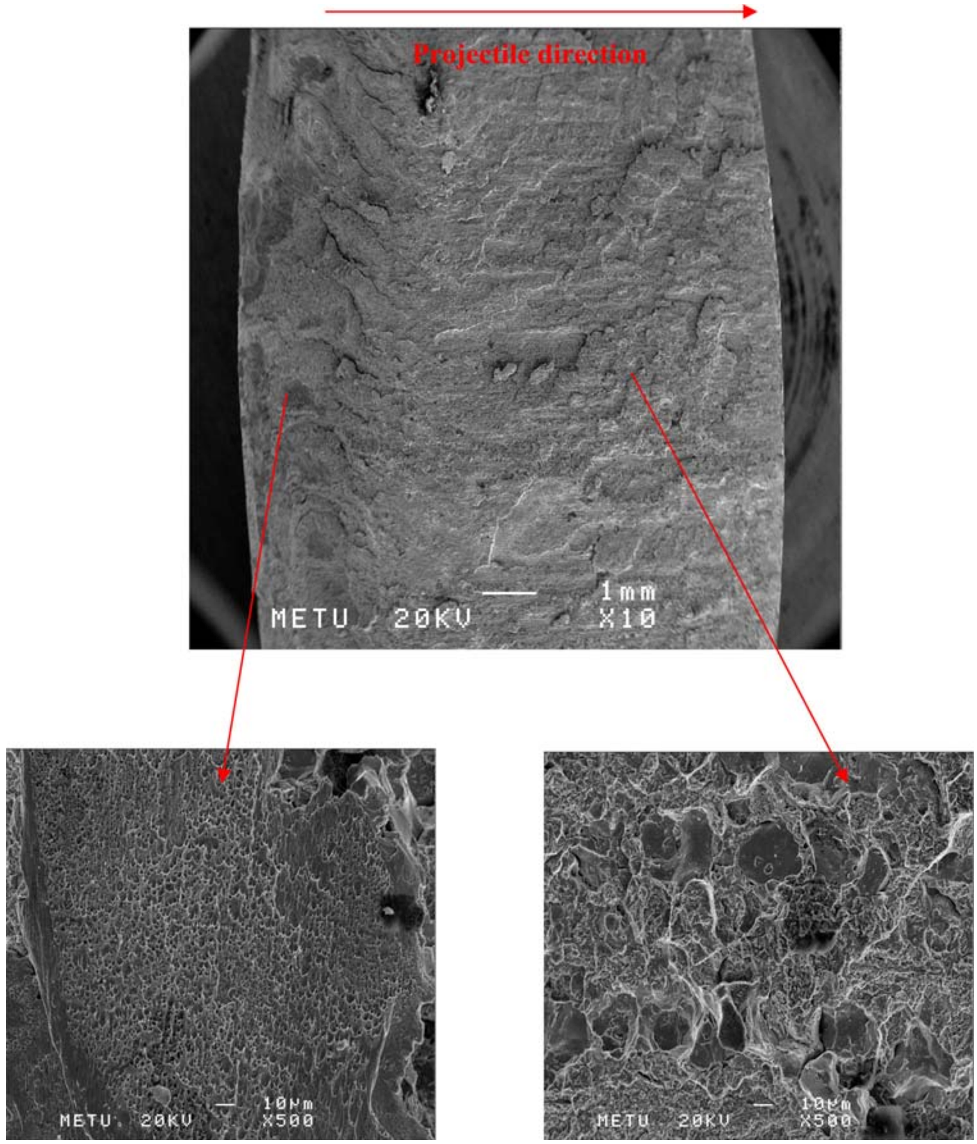

Fig. 9 Photos of the fracture surface of the specimen 2C3 by SEM

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