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RESEARCH PAPER

Influence of Using SiC and Al_2O_3 Ceramic Front Layer on Ballistic Performance of a Bainitic Steel: A Comparative Study

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Abstract

Development of lightweight armors is vital in order to provide ballistic protection in a more effective way. The weight of steel armor can be decreased significantly by setting a front ceramic layer on it. In this paper, the influence of utilizing SiC and Al_2O_3 ceramic front layer on the ballistic behavior of 4140 bainitic steel was investigated experimentally. All steel plates were initially subjected to the austempering treatment by applying the austenitization at 860 °C for 1 h and then holding in a salt bath at 343 °C for 50 min to get fully bainitic microstructure. And then, the laminated composites, consisting of SiC or Al_2O_3 front layer (50×50 mm in size) and bainitic steel backing layer, were prepared by joining these layers with an acrylic adhesive. After the mechanical and microstructural characterization of the bainitic steel, the ballistic shots were made using 7.62×51 mm AP projectile with an average speed of 788.4 m/s on both monolithic steel and layered armor samples for comparison. The samples, which stopped the bullet at normal impact condition without complete perforation or disintegration of the bainitic steel layer, were termed as successful. The bainitic steel achieved the ballistic protection at a thickness $\geq$ 14 mm but the use of SiC layer provided the weight saving of at least 42.9% and the Al_2O_3 front layer enabled the weight reduction of 28.6% in the armor with respect to the monolithic 4140 bainitic steel.

Keywords Bainitic steel · Armor · Laminated composite · Ceramic · Ballistics

Introduction

Human being has been trying to develop more effective defense systems, tools and materials against enemies or threats since the ancient times permanently. Although there were only a few number of materials available to be used in defense applications along with the stone age, the variety of engineering materials increased firstly with the advancement of metallurgy throughout the World. In order to get the higher protection levels in defense, stone, silk, wood, bone and leather had been largely or completely replaced initially with metallic counterparts such as bronze, iron and steel with the development of civilizations [1]. Some early major civilizations such as Egyptians, Sumerians, Assyrians, Greeks and Persians used the metallic armors including bronze, iron and steel in addition to the natural materials; linen, leather, wood and wool [1, 2]. In addition, The Great Hun Empire and Gokturks were very skillful about producing and shaping iron and they utilized the combined form of metal and leather to get the lightweight armors to enhance their mobility in wars [3]. Moreover, the advanced forms of metallic armor types were recorded in some other major civilizations such as The Roman Empire [2] and The Great Seljukians [4], during the Medieval Age, extensively. The utilization of firearms was spread from the 14th century very rapidly and it changed the strategy of defense and war significantly [5]. Europe, The Ottoman Empire and Japan were found to be very successful in production and deployment of firearms [5]. On the other hand, with the development of fast and massive steel production technologies during the first industrial revolution (1760–1840), utilization of steel started to increase rapidly in many different areas as well as defense industry [6]. The types of steel had further been increased tremendously by using different chemical compositions

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with various alloying elements (like Cr, Mo, Ni, Mn, Si, V, Co, W and Ti), heat treatment techniques and manufacturing processes to get predetermined mechanical properties as good as possible. During the World War I (1914–1918), the metallic helmets and breastplace were used widely while in the Second World War (1939–1945) laminates of fiberglass and polyester were utilized together with the steel plates [1, 2]. The advancement in the weapons (bombs, artillery shells, high speed projectiles, guns etc.) has triggered the need for more effective armor systems and materials or vice versa [1, 2].

The diversity of engineering materials increased very rapidly, especially in the 20th century by incorporating polymers, technical ceramics, composites and nanomaterials [7]. Nowadays, there are many candidate engineering materials to be used in armor applications [8] i.e., metals (steel, aluminum alloys, magnesium alloys, titanium alloys) [9, 10], ceramics (Al_2O_3, SiC, B_4C, TiB_2, ZTA, Si_3N_4) [9, 11], polymers (ultra high molecular weight polyethylene, aramid, poly(p-phenylenebenzobisoxazole)) [12], fiber reinforced composites [10, 12], laminated composites [13–15] and nanomaterials [16].

The armor material, providing the ballistic protection at possible lowest areal density, is strongly needed to be used for the protection of military vehicles, soldiers, buildings and so on. In addition to lightness, it should have multi-hit capability, high energy absorbance under impact and flexibility [1, 8]. Steel is still the most widely used engineering material in battle tanks due to its attractive mechanical properties, easy production methods, cheapness and large technological database [8]. Steels with sufficient amount of alloying elements such as Cr, Ni and Mo can get different mechanical properties upon forming a variety of phases after suitable heat treatment [17]. This enables the armor steel design for defense systems in a more flexible manner. The bainite phase of steel with a good combination of strength and toughness has a great potential to be used under either low or high velocity impact conditions [17]. In some recent studies, the bainitic steel (BS) has been evaluated as a new candidate steel armor [18–20]. Mishra et al. [18] investigated the ballistic performance of a nano-sized BS using the V_{50} and depth of penetration tests. They concluded that the BS, maintaining the complete ballistic protection at 120 kg/m^2, demonstrated much better performance than the ARMOX 500 [18]. In another study, Jo et al. [19] examined the effect of retained austenite (RA) amount on the ballistic behavior of high-strength BSs. They concluded that transformation induced plasticity (TRIP) which was gained from metastable RA enhanced the ballistic resistance of these steels [19]. Furthermore, Konca [20] studied the effect of bainitic and martensitic microstructures on the ballistic performance of RHA (MIL-A-12560) steel against 12.7 mm bullets. Although there was no direct correlation between hardness and ballistic strength found for the investigated samples, the higher ballistic performance was provided with bainitic microstructure compared to the tempered martensitic one in the steel [20]. In one of previous studies [21], the failure mechanisms of the BS subjected to the ballistic impact by 7.62 AP projectile were examined. The existence of adiabatic shear bands, cleavage type fracture and abrasion on the failed steel samples were detected after the impact [21]. On the other hand, the BS in the forms of perforated [22] or slotted armor [23] was also investigated. However, steel has a relatively higher density in comparison to polymers, fiber reinforced polymeric composites and most of ceramics and metals so that it would not be suitable to be accommodated in light structures or systems [7, 8]. On the other hand, the laminated composite, having ceramic front and metallic backing layers, comes into prominence to improve the ballistic efficiency compared to monolithic metallic armor, especially to be used in ground and air military vehicles [8]. In this type of material, hard ceramic layer significantly decreases the ballistic effect by blunting and fracturing projectile on impact [24, 25]. And also it spreads the impact energy of projectile to a greater area via its conoidal type fracture upon impact [24].

The ballistic protection ability of laminated composites strongly depends on mechanical properties of ceramic and metal layers [13, 14, 24, 25] as well as their bonding nature [26]. Hence, the influence of these important parameters on their ballistic performance should be clarified with the aid of real ballistic tests. According to the literature survey, there is no study made on the ballistic behavior of ceramic/BS layered structures. In addition, the works on the ballistic performance of BS are very limited [18–21]. In this paper, the ballistic characterization of the 4140 BS either in monolithic or laminated composite form was investigated against the 7.62 × 51 mm armor piercing (AP) projectile for comparison. Moreover, the ability of SiC and Al_2O_3 ceramic front layer on the enhancement of the ballistic success of the 4140 BS was examined with respect to areal density of armor.

Experimental Methods

Preparation of Samples

In this study, the 4140 steel plates with a diameter of 80 mm was selected in preparation of steel and laminated composite (SiC/BS and Al_2O_3/BS) armors. Meantime, the SiC and Al_2O_3 tiles, 50 × 50 mm in size, were used as a front layer in the laminated composites. The thickness of SiC and Al_2O_3 tiles was 8.5 and 9.3 mm, respectively whereas various steel

Table 1 The chemical composition of the 4140 steel (wt. %)

C	Si	Mn	Mo	Ni	Cr
0.38	0.22	0.69	0.20	0.03	0.97
P	S	V			
0.015	0.007	0.01			

Table 2 The nomenclature of BS samples with respect to thickness and areal density

Sample code	Thickness (mm)	Areal density (kg/m^2)
B0	6.0	47.0
B1	8.0	62.7
B2	10.0	78.4
B3	12.0	94.1
B4	14.0	109.8
B5	16.0	125.4
B6	18.0	141.1

Table 3 The nomenclature of laminated composites with respect to thickness and areal density

Sample code	Front layer (mm)	Backing layer (mm)	Areal density (kg/m^2)
S1	8.5	4.6	62.7
S2		6.6	78.4
S3		8.6	94.1
S4		10.6	109.8
S5		12.6	125.4
S6		14.6	141.1
A1	9.3	3.4	62.7
A2		5.4	78.4
A3		7.4	94.1
A4		9.4	109.8
A5		11.4	125.4
A6		13.4	141.1

thicknesses were used to get the same areal density at the steel and laminated composite armors for comparison. The chemical composition of the investigated steel can be seen in Table 1. And also, Tables 2 and 3 denote the code, thickness and areal density of steel and laminated composites, successively. In the codes of samples, B, S and A were used as the first letter to nominate the monolithic BS, SiC/BS and Al_2O_3/BS laminated composites, successively.

Table 4 The mechanical properties of acrylic based adhesive [28]

Tensile strength (MPa)	(%) elongation	E (MPa)
~ 7.7	~ 3.5	462

The density of SiC and Al_2O_3 tiles which was measured using the Archimedes' principle [27] was recorded to be 3.10 and 3.86 g/cm^3, respectively. All steel plates used in either monolithic or laminated composite armors were subjected to austempering treatment to get the fully bainitic microstructure. In this process, they were initially austenitized at 860 °C for 1 h in a well-type furnace under endo gas atmosphere. And then, they were immediately transferred into a salt bath containing $Ba(NO_3)_2$ and NaCN and hold at 343 °C for 50 min to provide austenite to bainite transformation. After that, the steel samples were taken out from the salt bath and cooled in air. Next, the composites were prepared by joining the ceramic and steel layers with an acrylic adhesive whose properties are given in Table 4 [28]. Figure 1 shows the typical Al_2O_3/BS and the SiC/BS samples after joining treatment.

Microstructural Examination

The microstructure of steel was investigated with the aid of an optical microscope (Olympus BX51) after an etching with 3% nital for 60 s. Moreover, the failed steel layers after the ballistic testing of armor samples were also subjected to microstructural characterization to observe the variations along with the deformation zone (Fig. 2).

Mechanical Testing

The hardness, impact and tensile tests were made to determine steel's main mechanical properties. The Rockwell C hardness of all steel plates was determined using a macro hardness testing device (BMS DIGIROCK-RBOV). In addition, the tensile testing was carried out with the help of a universal tension-compression testing machine (DARTEC-MTS) according to TS EN ISO 6892-1 [29]; while Charpy impact testing was made with an impact testing machine

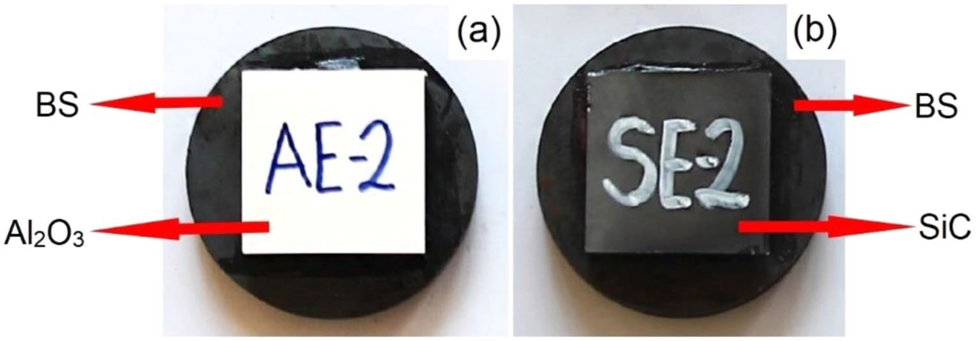

Fig. 1 The picture of laminated composite samples after bonding with the adhesive **(a)** Alumina/BS, **(b)** SiC/BS

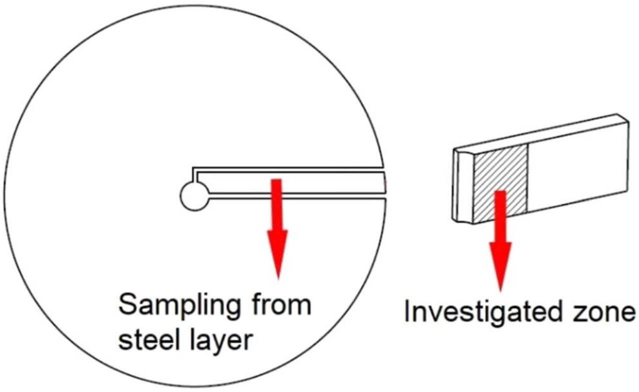

Fig. 2 The investigated zone on the steel sample, just near deformation zone created by the projectile, after the ballistic testing

(ALŞA 450 CE) in compliance with TS EN ISO 148-1 [30]. All the mechanical testing samples were subjected to the austempering treatment prior to the tests.

Ballistic Testing

The ballistic testing of BS, Al_2O_3/BS and SiC/BS composites was conducted using 7.62 × 51 mm AP projectile (steel cored) in a ballistic testing laboratory in Türkiye. This type of projectile is very common and widely distributed in army forces throughout the World [31]. The distance between the projectile exit and target was kept as 16 m (Fig. 3). Furthermore, the target armors were subjected to normal impact by projectile at an average velocity of 788.4 m/s. The single-shot ballistic tests were made three times for each sample type individually. The probability of perforation was calculated out of three shots for every specimen. Therefore three identical samples were tested for each case under the impact of 7.62 × 51 mm AP projectile separately to find out the ballistic protection ability. The samples, that made the bullet ineffective at normal impact condition without complete perforation or disintegration of the bainitic steel layer, were designated as successful.

Experimental Results and Discussion

Mechanical and Microstructural Properties

The average hardness of steel plates out of 5 measurements was measured as 39.3 HRC. Meantime, the hardness of SiC tile was ~2483 HV [28] while that of Al_2O_3 tile was around ~1900 HV [13]. In addition, the yield and tensile strength of the steel were found to be 1282 and 1511 MPa, respectively. Meanwhile the BS's ductility was obtained to be 15.5%. Figure 4 shows the specimens after tension testing in which the plastic deformation and necking are clearly visible due to the steel's moderate ductility. Moreover, the average impact toughness of the BS was recorded as 30.1 J. The samples after the impact testing are illustrated in Fig. 5. The fibrous nature of the fracture surfaces of tested samples is apparently observed. Furthermore, the microstructure of the austempered steel is depicted in Fig. 6. The steel has mainly the lower bainitic phase with some RA.

Ballistic Test Results and Discussion

Bainitic Steel Armor

The full ballistic protection was provided with the BS having a thickness ≥ 14 mm. In other words, it can be reached with an areal density ≥ 109.8 kg/m^2 for the monolithic BS. Table 5 lists the protection ability of BS armor with respect

Fig. 3 The schematic view of the ballistic testing setup showing the location of rifle, velocity sensors and target

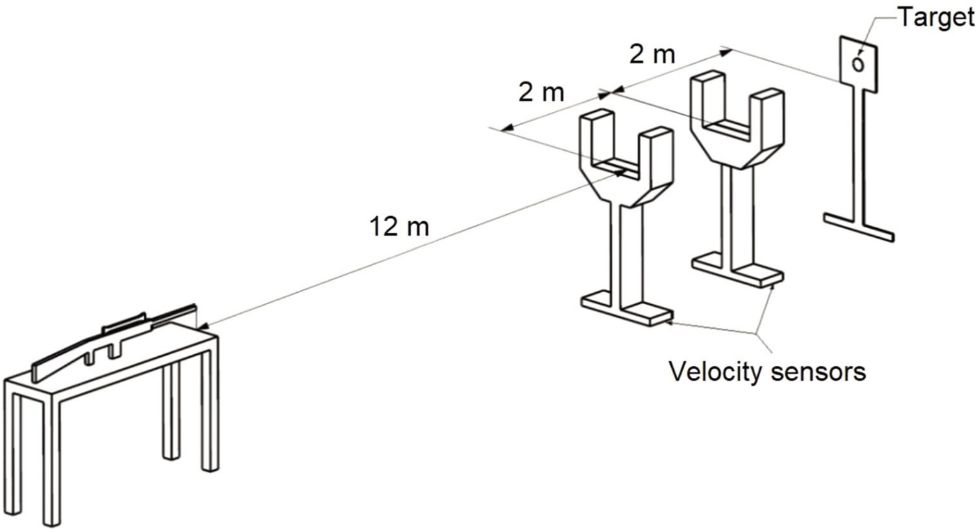

Fig. 4 Tensile specimens of bainitic steel after the tensile testing

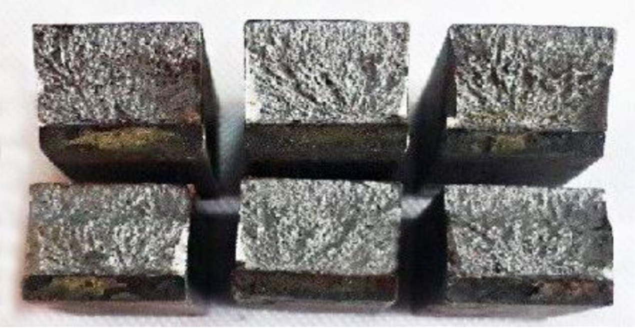

Fig. 5 The fibrous nature of fracture surfaces of impact specimens after the impact testing

to its thickness under the hit of projectile. Figure 7 illustrates the sample pictures after the ballistic testing. The main deformation mechanism was recorded to be ductile hole formation for the failed samples. This mechanism is typically observed for ductile metallic armors commonly [32]. It reflects the adequate ductility and toughness of BS against the ballistic threat of 7.62 mm AP projectile in the failed samples to resist on extensive crack formation, pulverization or brittle fracture after the impact. However, the radial cracks at the rear side of some steel samples were also observed when the projectile was unable to perforate them (Fig. 8). The armor should prevent the perforation and even penetration of projectile by eroding and breaking it into ineffective small parts. It should absorb the energy of projectile upon impact without losing its integrity to be able to withstand multi-hit. When projectile impacts target metal, the response of armor will change according to its mechanical properties, properties of projectile and ballistic speed. The energy of projectile will be dissipated by metallic armor through ductile hole formation, fragmentation, brittle fracture, petalling, radial cracking or plug formation in the course of penetration and/or perforation of projectile [32].

Table 5 The probability of perforation of the BS samples against 7.62 mm AP projectile

Sample	Thickness (mm)	Probability of perforation (%)
B0	6	100
B1	8	100
B2	10	66
B3	12	66
B4	14	0
B5	16	0
B6	18	0

Table 6 lists the ballistic test results for some steels against the 7.62 mm AP projectile that were found in various studies [18, 33–36]. In a previous study [33], the lowest areal density for the 4140 type tempered martensitic steel providing the full ballistic success against the 7.62 AP projectile was recorded to be 100 kg/m^2 when its hardness was about 53 HRC. However, it was obtained that if the 4140 martensitic steel was tempered to ~38, 50 or 60 HRC, it failed even at 115 kg/m^2 in a brittle manner [33]. In another study [34], AISI 4340 and 100Cr6 steels with the tempered martensite microstructure provided the ballistic protection against the same threat at an areal density ≥ 70 and 100 kg/m^2, successively. It is interesting to specify that when the 4340 martensitic steel was tempered to 39.5 HRC, it provided the ballistic protection at 115 kg/m^2 [34]. Furthermore, the 100Cr6 tempered martensite steel did not

Fig. 6 The microstructures of BS before the ballistic testing **(a)** 500X **(b)** 1000X

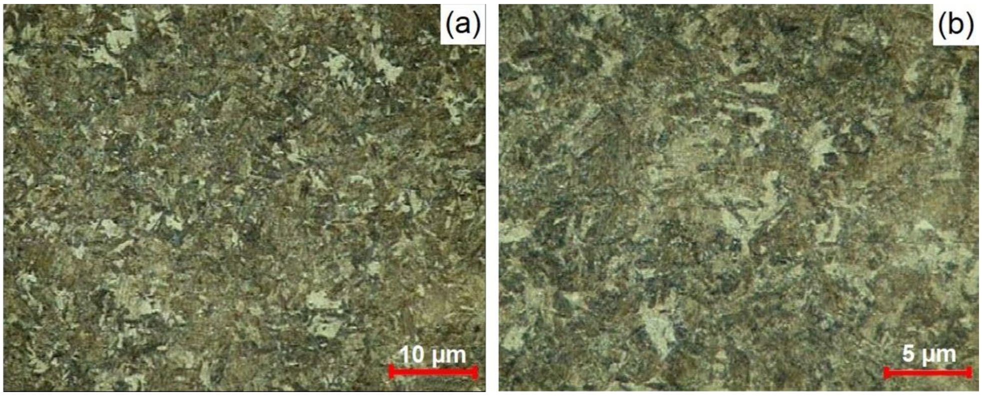

Fig. 7 The front and back views of BS samples after the ballistic shot **(a)** B0, **(b)** B1, **(c)** B2, **(d)** B3, **(e)** B4, **(f)** B5, **(g)** B6

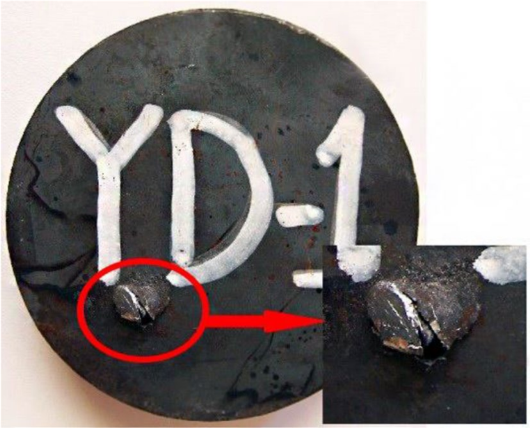

Fig. 8 Radial crack formation at the rear side of B3

show the successful ballistic resistance even at 115 kg/m^2, when its hardness was 49, 57 or 60 HRC. This was attributed to its very low ductility values of 8.7, 6.0 and 5.1% at these hardness levels, successively [34]. The higher ballistic performance of the 4140 BS in comparison to some of these tempered martensitic steels [33, 34] was ascribed to its good combination of strength, hardness and ductility. And also, it was proposed that the TRIP mechanism, induced by metastable RA in the BSs under the ballistic impact, decreased the generation of adiabatic shear bands (ASBs) and improved the ballistic efficiency [19]. Hence, it was considered that the RA contributed to the improvement on the ballistic strength of the 4140 BS by this mechanism. On the other hand, Übeyli et al. [36] investigated the effect of martensite volume fraction on the ballistic efficiency of a low alloy steel. They deduced that the ballistic performance improved with an increase in martensite volume fraction of the steel and the steel having 72 vol% martensite withstood the projectile without any perforation at an areal density ≥ 118 kg/m^2. Although the 4140 BS had the ballistic performance inferior to some tempered martensitic steels [33–35], it exhibited superior ballistic resistance compared to the dual phase steel [36]. The exact comparison of the 4140 BS with the nano BS [18] can't be done as the velocity of projectile used at the ballistic testing of nano BS was 850 m/s [18] which is higher than that in the current study.

Table 6 The ballistic performance levels of different steels under the impact of 7.62 mm projectile

Steel/phase	Yield strength (MPa)	Tensile strength (MPa)	Hardness	Velocity of projectile (m/s)	Areal density (kg/m^2)	Ref.
4140/Tempered Martensite	1400	1640	53.4 HRC	782	100	[33]
100Cr6/Tempered Martensite	1200	1570	40.4 HRC	779	100	[34]
4340/Tempered Martensite	1300	1600	49.5 HRC	779	70	[34]
50CrV4/Tempered Martensite	1490	1700	60 HRC	805	89	[35]
Dual phase steel/ 72% Martensite 28% Ferrite	-	-	438 HV	786	118	[36]
Carbide Free Nano Bainitic steel	1450	2050	600 HV	850	120	[18]
4140/Bainite	1282	1511	39.3 HRC	788.4	109.8	Current work

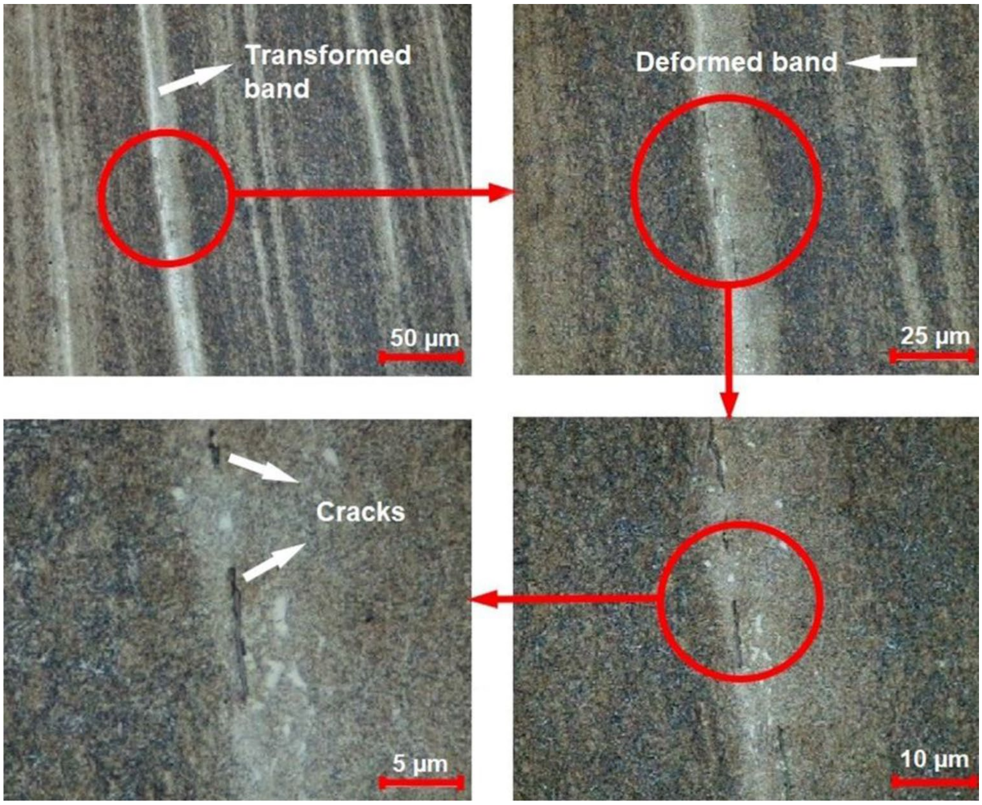

Fig. 9 The adiabatic shear bands (transformed and deformed) and some cracks formed within the BS after the ballistic test

High velocity impact leads to some important microstructural changes by the generation of ASBs in metals. These bands are classified as deformed (having highly sheared grains) and transformed (with a phase change) bands are commonly observed in the metals [37]. There is no enough time to transfer the heat generated within the deformation zone upon dynamic impact so that there is a rapid and local temperature increment which results in the existence of these bands. Both types of bands are also seen in the BSs subjected to the ballistic testing (Fig. 9). Cracks, triggering the fracture, were also detected along with the transformed (white colored) bands. In one of the former studies [38], the finer grains together with carbide precipitates that led to a hardness increment compared to main steel structure were recorded in the transformed bands, due the thermo-mechanical instability under the high strain rate [37].

Laminated Composite Armor

The SiC faced BS armors exhibited a very good performance under the ballistic impact.

(Table 7). All the samples were recorded to be successful and there were no penetration, perforation or plastic deformation occurred at the BS layer. Silicon carbide ceramic tile owing to its very high hardness was very effective in blunting and fracturing the projectile in the case of impact as expected. On the other hand, the ceramic front layer assists in improving the ballistic resistance by dissipating

Table 7 The ballistic results of the SiC faced BS under the hit of 7.62 mm projectile

Sample	Backing steel layer (mm)	Probability of perforation (%)
S1	4.6	0
S2	6.6	0
S3	8.6	0
S4	10.6	0
S5	12.6	0
S6	14.6	0

Table 8 The ballistic results of the alumina faced BS against 7.62 mm AP projectile

Sample	Backing steel layer (mm)	Probability of perforation (%)
A1	3.4	33
A2	5.4	0
A3	7.4	0
A4	9.4	0
A5	11.4	0
A6	13.4	0

the projectile's kinetic energy to a greater area on the backing steel layer via forming a conoidal fragment upon impact [24].

Figure 10 depicts the images of the SiC/BS composites after the ballistic test. The SiC tiles were fractured to small pieces when the projectile hit but there is no penetration and even plastic deformation observed on the BS plates. The SiC/BS composite maintained the complete ballistic success at an areal density of 62.7 kg/m^2. Moreover, it has also a potential for full ballistic protection even at lower areal density ($\leq$62.7 kg/m^2). The use of SiC layer provided the weight saving of at least 42.9% in the armor compared to the monolithic 4140 BS.

Table 8 presents the ballistic test data for the alumina/BS composites. It can be seen that only one third of the sample with the areal density of 62.7 kg/m^2 failed by the projectile while the others provided the full ballistic protection. Therefore, the alumina/BS composite accomplished to make the projectile inefficient at an areal density $\geq$78.4 kg/m^2. Figure 11 illustrates the tested alumina/BS composites. Although the two third of AB samples enabled the full protection, their backing layers were plastically deformed during the absorption of the remaining energy of projectile (Fig. 12). The alumina front layer contributed to the weight reduction of 28.6% in the armor in comparison to the 4140 BS. The adhesive under the shock waves created by the

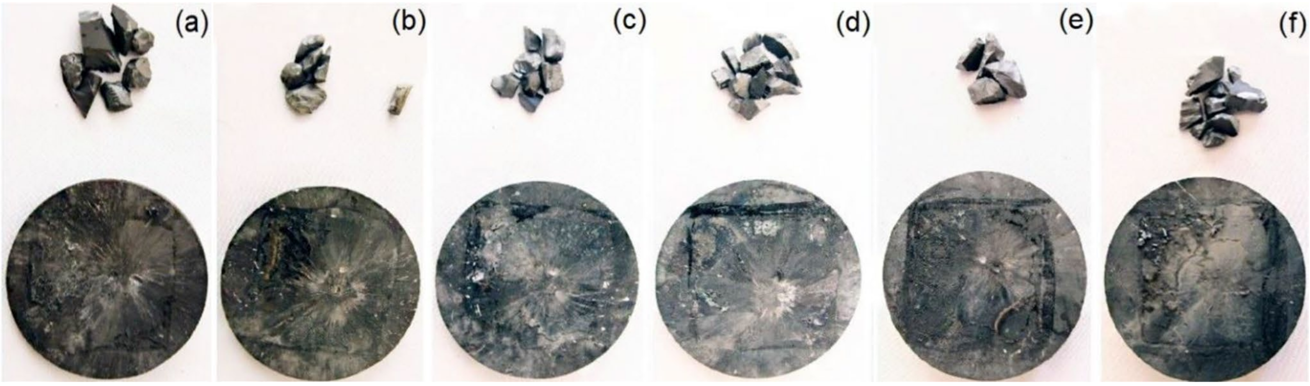

Fig. 10 The pieces of broken SiC tile and undeformed steel rear layer of SiC/BS samples after the ballistic test **(a)** S1, **(b)** S2, **(c)** S3, **(d)** S4, **(e)** S5, **(f)** S6

Fig. 11 The particles of broken alumina ceramic tile and successful bainitic steel layer of alumina/BS samples after the ballistic test **(a)** A1, **(b)** A2, **(c)** A3, **(d)** A4, **(e)** A5, **(f)** A6

Fig. 12 The plastic deformation taken place at the steel layer of A1 sample **(a)** A1-2 **(b)** A1-3

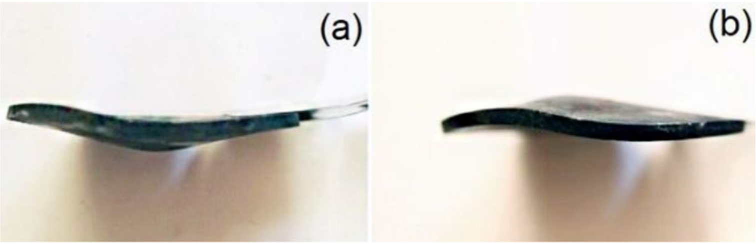

Table 9 The ballistic protection levels of some laminated composites against 7.62 mm AP projectile for comparison

Front layer	Backing layer/phase(s)	Areal density (kg/m^2)	Velocity of 7.62 mm AP projectile (m/s)	Ref.
Alumina	4340 steel Tempered martensite	55	785	[14]
Alumina	Dual phase steel 72% Martensite 28% Ferrite	94	789	[39]
Alumina	4140 Bainite	78.4	788.4	Current research
SiC	34CrNiMo6 Tempered martensite	54.6	778.5	[28]
SiC	4140 steel Bainite	62.7	788.4	Current research

momentum of the projectile upon impact was not able to hold the SiC or the alumina ceramic pieces.

A comparison between the current and some previous results [14, 28, 39] related to the ballistic performance of SiC or Al_2O_3 faced steel composites against the 7.62 mm AP projectile is given in Table 9. The 4140 BS as a backing layer showed the better ballistic strength than dual phase steel [39]. This is attributed to the higher toughness of the bainitic steel relative to the dual phase steel [39]. However, its performance was found to be lower than some tempered martensitic steels [14, 28]. Özer [28] used the 8.5 mm thick SiC front layer (as in the current study) in SiC/34CrNiMo6 steel composites for ballistic tests. The higher hardness and tensile strength of 34CrNiMo6 steel (~51 HRC and 1847 MPa) [28] compared the 4140 bainitic steel were responsible for its higher ballistic performance. This is due to the fact that the compressive stress waves generate on target material upon impact of projectile and reflect back in the form of tensile waves [40]. For this reason, the backing material should have high tensile strength and toughness to handle these waves without fracturing. On the other hand, Demir et al. [14] utilized the 6 mm thick alumina in the alumina/4340 steel composites. Even though the hardness and tensile strength of the rear 4340 steel layer (tempered at 580 °C) [14] were close to those of the 4140 bainitic steel, the remarkable difference in the ballistic resistance of these composites was ascribed to the lower ceramic/metal thickness ratio used in this study. The ceramic/metal thickness ratio is a critical variable which should be taken into account for comparison since the ballistic behavior of laminated composites varies with this ratio for the same areal density substantially [25, 41, 42]. Hence, the comparison of different laminated composites should be done by keeping it constant.

Conclusions

The ballistic behavior of the 4140 BS together with the SiC/4140 BS and the Al_2O_3/BS laminated composites was examined by utilizing 7.62 mm AP projectile at normal impact.

- The monolithic BS maintained the ballistic protection successfully at the thickness of 14 mm corresponding to the areal density of 109.8 kg/m^2.
- The ballistic performance of the 4140 BS was found to be superior to some tempered martensitic steels [33, 34] and dual phase steel [36].
- The use of ceramic layers was very effective in the reduction of areal density of BS armor required to get rid of the ballistic threat with the 7.62 mm AP projectile.
- The SiC/BS composite achieved the complete ballistic success at an areal density of 62.7 kg/m^2. Moreover, it has also a potential for full ballistic protection even at lower areal density ($\leq$62.7 kg/m^2) since all the SiC/BS samples were obtained to be successful. For this reason, the use of SiC layer provided the weight saving of at least 42.9% in the armor compared to the monolithic 4140 BS.

- The alumina/BS composite succeeded to make the projectile inefficient at an areal density $\geq$78.4 kg/m^2 without any perforation or penetration.
- The optimization of laminated composites by changing the thickness ratio of ceramic to metal [25, 41, 42] could be done in further studies for the additional benefit in terms of lowering weight of armor.

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Data availability The raw data of tests is available upon request.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Yadav R, Naebe M, Wanga X, Kandasubramanian B (2016) Body armour materials: from steel to contemporary biomimetic systems. RSC Adv 6:115145–115174. https://doi.org/10.1039/C6RA24016J
2. Laible RC, Barron E (1980) History of armor. In: Laible RC (ed) Ballistic materials and penetration mechanics. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands, pp 9–40
3. Nişancı H (2018) Soldiership in Steppe Turks. M.S. Thesis. Mimar Sinan University, Institute of Social Sciences, İstanbul, Türkiye
4. Çerikan Uğur F (2014) Iron in Turkish Culture. PhD. Thesis. Pamukkale University, Institute of Social Sciences, Turkish Language and Literature, Denizli, Türkiye
5. Chase K, Firearms (2003) A Global history to 1700. Cambridge University Press, Cambridge, UK
6. Mohajan HK (2019) The first industrial revolution: creation of a new global human era. Int J Soc Sci Humanit 5(4):377–387
7. Balasubramanian M (2014) Composite materials and Processing. CRC, Boca Raton, FL, USA
8. Hazell PJ (2023) Armour: materials. Theory and design. CRC, Boca Raton, FL, USA
9. Balos S, Howard D, Brezulianu A, Zlatanovic DL (2021) Perforated plate for ballistic protection - A review. Metals 11(4):526. https://doi.org/10.3390/met11040526
10. Bhat A, Naveen J, Jawaid M, Norrrahim MNF, Rashedi A, Khan A (2021) Advancement in fiber reinforced polymer, metal alloys and multi-layered armour systems for ballistic applications - a review. J Mater Res Technol 15:1300–1317. https://doi.org/10.1016/j.jmrt.2021.08.150
11. Andraskar ND, Tiwari G, Goel MD (2022) Impact response of ceramic structures - a review. Ceram Int 48(19):27262–27279. https://doi.org/10.1016/j.ceramint.2022.06.313
12. Tam T, Bhatnagar A (2006) High performance ballistic fibers. In: Bhatnagar A (ed) Lightweight ballistic composites: military and law-enforcement applications. Woodhead Publishing Limited, Cambridge, England, pp 1–39
13. Übeyli M, Yıldırım RO, Ögel B (2008) Investigation on the ballistic behavior of Al$_2$O$_3$/Al2024 laminated composites. J Mater Process Technol 196(1–3):356–364. https://doi.org/10.1016/j.jmatprotec.2007.05.050
14. Demir T, Übeyli M, Yıldırım RO, Karakaş MS (2009) Response of alumina/4340 steel laminated composites against the impact of 7.62 mm armor piercing projectiles. Sci Eng Compos Mater 16(2):89–98. https://doi.org/10.1515/SECM.2009.16.2.89
15. Ayvaz M, Çetinel H (2021) Ballistic performance of powder metal Al5Cu-B$_4$C composite as monolithic and laminated armor. Mater Test 63(6):512–518. https://doi.org/10.1515/mt-2020-0084
16. Wu S, Sikdar P, Bhat GS (2023) Recent progress in developing ballistic and anti-impact materials: nanotechnology and main approaches. Def Technol 21:33–61. https://doi.org/10.1016/j.dt.2022.06.007
17. Krauss G (2005) Steels: Processing, structure and performance. ASM International, Ohio, USA
18. Mishra B, Sukumar G, Senthil PP, Reddy PRS, Singh BB, Ramakrishna B, Kumar KS, Madhu V (2023) Ballistic efficacy of carbide free high strength nano-structured bainitic armour steels. Def Sci J 73(2):131–139. https://doi.org/10.14429/dsj.73.18634
19. Jo MC, Kim S, Suh DW, Kim HK, Kim YJ, Sohn SS, Lee S (2021) Enhancement of ballistic performance enabled by transformation-induced plasticity in high-strength bainitic steel. J Mater Sci Technol 84:219–229. https://doi.org/10.1016/j.jmst.2020.12.059
20. Konca E (2020) A comparison of the ballistic performances of various microstructures in MIL-A-12560 armor steel. Metals 10(4):446. https://doi.org/10.3390/met10040446
21. Atapek SH, Karagoz S (2011) Ballistic impact behaviour of a tempered bainitic steel against 7.62 mm armour piercing projectile. Def Sci J 61(1):81–87. https://doi.org/10.14429/dsj.61.411
22. Burian, W, Żochowski P, Gmitrzuk, Marcisz, J, Starczewski, L, Juszczyk, B, Magier, M (2019) Protection effectiveness of perforated plates made of high strength steel. Int J Impact Eng 126:27–39. https://doi.org/10.1016/j.ijimpeng.2018.12.006
23. Fras T, Murzyn A, Pawlowski P (2017) Defeat mechanisms provided by slotted add-on bainitic plates against small-calibre 7.62 mmx51 AP projectiles. Int J Impact Eng 103:241–253. https://doi.org/10.1016/j.ijimpeng.2017.01.015
24. Wilkins ML (1978) Mechanics of penetration and perforation. Int J Eng Sci 16(11):793–807. https://doi.org/10.1016/0020-7225(78)90066-6
25. Hetherington JG (1992) The optimization of two component composite armors. Int J Impact Eng 12(3):409–414. https://doi.org/10.1016/0734-743X(92)90145-J
26. Zaera R, Sánchez-Sáez S, Pérez-Castellanos JL, Navarro C (2000) Modelling of the adhesive layer in mixed ceramic/ metal armours subjected to impact. Compos Part A: Appl Sci Manuf 31(8):823–833. https://doi.org/10.1016/S1359-835X(00)00027-0
27. ASTM B962-17 Standard test methods for density of compacted or sintered powder metallurgy (PM) products using Archimedes' principle
28. Özer E: Effect of heat treatment and SiC front layer on the ballistic behaviour of 34CrNiMo6 steel., Thesis MS (2015) Osmaniye Korkut Ata University, Institute of Natural and Applied Science, Osmaniye, Türkiye
29. TS EN ISO 6892-1 Metallic materials– Tensile Testing - Part 1: Method of test at room temperature
30. TS EN ISO 148-1 Metallic materials - Charpy pendulum impact test - part 1: Test Method
31. Bhatnagar A (2006) Bullets, fragments and bullet deformation. In: Bhatnagar A (ed) Lightweight ballistic composites: military and law-enforcement applications. Woodhead Publishing Limited, Cambridge, England, pp 87–114
32. Rosenberg Z, Dekel E (2012) Terminal ballistics. Springer, London
33. Demir T, Übeyli M, Yıldırım RO (2008) Investigation on the ballistic impact behavior of various alloys against 7.62 mm armor piercing projectile. Mater Des 29(10):2009–2016. https://doi.org/10.1016/j.matdes.2008.04.010

34. Demir T, Übeyli M, Yıldırım RO (2009) Effect of hardness on the ballistic impact behavior of high-strength steels against 7.62-mm armor piercing projectiles. J Mater Eng Perform 18(2):145–153. https://doi.org/10.1007/s11665-008-9288-3
35. Übeyli M, Yıldırım RO, Ögel B (2007) On the comparison of the ballistic performance of steel and laminated composite armors. Mater Des 28(4):1257–1262. https://doi.org/10.1016/j.matdes.2005.12.005
36. Übeyli M, Demir T, Deniz H, Yıldırım RO, Keleş Ö (2010) Investigation on the ballistic performance of a dual phase steel against 7.62 mm AP projectile. Mater Sci Eng A 527(7–8):2036–2044. https://doi.org/10.1016/j.msea.2009.11.040
37. Dormeval R (1987) The Adiabatic Shear Phenomenon. In: Blazynski TZ (ed) Materials at high strain rates. Elsevier Applied Science, pp 47–69
38. Übeyli M, Demir T, Yıldırım RO, Aycan MF (2009) Effect of heat treatment on the formation of adiabatic shear bands in high strength steels impacted by AP projectiles. Kovove Mater 47(6):409–413
39. Deniz H: Investigation on the ballistic behavior of a dual phase steel against 7.62 mm armor piercing projectile., Thesis MS (2009) Gazi University, Institute of Science and Technology, Mechanical Engineering
40. Meyers MA (1994) Dynamic behavior of materials. John Wiley & Sons Inc., New York
41. Wang B, Lu G (1996) On the optimisation of two-component plates against ballistic impact. J Mater Process Technol 57(1–2):141–145. https://doi.org/10.1016/0924-0136(95)02050-0
42. Lee M, Yoo YH (2001) Analysis of ceramic/metal armour systems. Int J Impact Eng 25(9):819–829. https://doi.org/10.1016/S0734-743X(01)00025-2