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A FRACTOGRAPHICAL STUDY ON BORON ADDED ARMOR STEEL DEVELOPED BY ALLOYING AND HEAT TREATMENT TO UNDERSTAND ITS BALLISTIC PERFORMANCE

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ABSTRACT

Fractographical examinations present a good relationship between fracture surface topography and basic rupture mechanism. Fracture consists of crack formation (crack nucleation) and crack growth (crack propagation). Many parametres such as type of loading, sensitivity of materials to crack play an important role on failure. Fracture in engineering alloys can occur by a transgranular (through the grains) or an intergranular (along the grain boundaries) fracture path.

In this study newly developed boron added armor steel has been rolled to form sheet product. Heat treatment series including austenitization, quenching and then tempering have been applied on boron added armor steel respectively. The effects of formed microstructures on mechanical properties have been studied extensively. Furthermore failure mechanism has been determined through fractografical examinations by using Scanning Electron Microscopy (SEM). due to its high resolution. In general SEM examinations are an important part of failure analysis.

Failure analysis and type of fracture provide also a good approach to understand the ballistic behaviour of armor steel. When the material is exposed to any kind of impact loading as performed by kinetic penetrator etc., it is obvious that the failure mode will give information about its ballistic performance.

KEY WORDS

Armor Steels, Boron Alloying, Microstructure, Fractography, Crack Formation.

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INTRODUCTION

The performance of steels depends on the properties associated with their microstructures, that is type, volume fraction, size, morphology (form factor) and area distribution of the various phases involved. Because all the phases in steels are crystalline, steel microstructures are made up of various crystals, sometimes as many as three or four different types which are physically blended by solidification, solid-state phase transformation, hot/cold deformation and heat treatment. Each type of microstructure is developed to a characteristic property range by specific processing route that control the microstructural changes. Thus processing technologies are used to tailor final microstructure.

Typical armour steels contain carbide forming elements, usually molybdenum and chromium and austenite forming elements, e.g. manganese and nickel with some carbon. Armored steels which are primarily used as cast and rolled material could be microalloyed with niobium, titanium and vanadium in double combination when subjected to thermomechanical treatment. Table 1 shows the composition of mostly used armor steels in military application all around the world. Table 2 represents the mechanical properties of armor steels denoted in Table 1.

During solidification of the melt primary MC and secondary M_7C_3 and $M_{23}C_6$ form. M_7C_3 ile $M_{23}C_6$ carbides go easily into solution at lower austenitization temperatures, but for MC carbides higher austenitization temperatures are needed.

In general to obtain a high hardness during tempering it is desired that high amounts of elements like Mo and Cr should dissolve during austenitization. At the given alloying level the expected theoretical amount of secondary hardening carbides (mainly due to Cr and Mo) is shown in Fig.1 [1]. Fig. 1 presents some medium and high alloyed steels where the main hardening is due to precipitation of very fine carbides during tempering (which are the so-called secondary hardening precipitates). Main matrix hardness is given by α-phase and alloying elements in the solid solution after tempering. Upon this, matrix hardness developes by the amount of secondary hardening precipitation during tempering. Armor steels belong also to the group of quench and tempered steels and their location is shown in this diagramm depending on the alloying level.

The working principle of a typical armor material depends on the reality of stopping the attack by the sharp tip of steel or other heavy metal based penetrator, with its high hardness. In order to understand the behaviour of an armour steel to a given armor penetrator, the concepts such as shock, deformation and fracture during penetration and perforation must be known [2-3]. As hardness and strength of armor steel increase, penetration resistance will also increase. The performance is directly related to fracture mode that is effective at specific levels of hardness. Fig. 2 presents schematically the general relationship between hardness and ballistic performance for steels [4].

At low values of hardness, plastic flow of the target controls performance and the steel fails by ductile hole formation (*Mode A*). As target strength increases localized failure of the material by through-thickness, adiabatic shear becomes more likely, ballistic performance may then be degraded when the target fails by plugging (*Mode B*). The point at which this transition occurs, and the magnitude of the degradation will depend not only on the quality and grade of steel, but also on the geometries of both target and projectile. For example, cleaner steels manufactured by electro slag refining as compared to conventional steelmaking routes, have been shown to delay this transition. Steels offer one clear advantage over many materials because of their greater strength potential. They can be hardened to such a level that an armor piercing projectile can be made to shatter upon impact, especially at high angles of attack. This catastrophic defeat of the projectile can, not suprisingly perhaps, leads to an improvement or recovery in ballistic performance, even though the target still fails eventually by plugging (*Mode C*). Mode C has been designated ‘hard plugging’ to differentiate it from Mode B, which is termed ‘soft plugging’. In Mode B, some plastic deformation of the target occurs before the onset of plugging; this leaves a witness of the nose of the projectile in the front-surface of the plug. In Mode C, however, no initial plastic deformation of the target occurs and a large amount of the kinetic energy of the projectile is dissipated as it shatters. The projectile can only then penetrate as a blunt-nosed object. As a result, a nearly perfect cylinder of the target material is ejected. In general, the harder the target, the larger the amount of projectile erosion and deformation, and the better the ballistic performance. Still further up the hardness scale, there is a natural upper limit to this relationship; when toughness has diminished to such a low level, the target itself simply shatters in a very brittle fashion and offers no structural support (*Mode D*).

The aim of fractography is to analyse fractured objects. Fractographical examinations present a good relationship between the resulting fracture surface topography and basic rupture mechanism. There are essentially four basic fracture modes: dimple rupture, cleavage, fatigue and decohesive rupture. In this study the fracture surface characteristics and some of the mechanisms associated with the fracture modes (especially dimple rupture and also cleavage) will be presented and illustrated [5].

On the other hand, ballistic test is required to determine the protection degree of an armor steel under impacts. An armor steel must provide some mechanical properties such as adequate strength, hardness and toughness. Applied heat treatment can modify all of these properties. Hence developed properties will present a good combination of mechanical properties. To understand ballistic behaviour of an armor, fractographical properties under dynamic and cyclic loading must be known.

In the ballistic industry, performance is generally determined with velocity, V_{50} for projectile impacts on heat treated armor plate (Fig. 3). The V_{50} ballistic test limit is the average of 10 fair impact velocities consisting of the five lowest complete penetration velocities and five highest partial penetration velocities provided that the spread for the 10 velocities is not greater than an allowable range of 150 feet per second (fps). If the 10-round average cannot be attained within allowable range, the ballistic plate is retested. The V_{50} ballistic limit is determined for a given size steel fragment by averaging the V_{50} test results for three test plates [6, 7, 8, 9].

EXPERIMENTAL STUDY

In this study microstructural and mechanical changes of a newly developed boron added armor steel with a given composition has been investigated by performing different heat treatments. Furthermore fractographical examination of these steels are done to get an idea of its ballistic performance under dynamic loading (e.g. attack of projectile).

The chemical composition of the steel used in experimental study is listed in Table 3. The reason of the element selection in the newly designed alloy is given below:

• Carbon	It is limited to weight-% 0.4 as in other standart armor steel compositions due to weldability.
• Manganese	It is limited to weight-% 0.2 for convenient controlling of segregation.
• Silicon	The amount is due to its being a standart accompanying element.
• Chrome	It is a readily dissolvable secondary carbide former. This element is responsible for a rapid formation of secondary hardening precipitates.
• Molybdenum	It is an element that increase the strength of steel by formation of fine M_2C precipitates with the incorpotation of chromium during tempering.
• Cobalt	It is an element with a high toughening effect on steel matrix.
• Nb+V+Ti	These elements are microalloying elements that form dinamically fine carbide precipitates during thermomechanical treatment.
• Boron	It has a high cross-section hardening contribution to the steel with a strong effect on strengthening due to formation of boride/carboboride.

The experimental steel has been cast with a medium frequency furnace (AEG furnace with a capacity of 550kg) in 7th Maintenance Center of Turkish Land Forces Command. After casting, plates sized 500x550x55 mm have been rolled 4.4 times. After this deformation the sheet has reached a size of 1500x600x12.5 mm.

Microstructural Characterization

All samples have been prepared by grinding with 320, 600 and 1000 mesh SiC abrasives respectively and then surface of samples have been polished with a 3µm diamond paste. Etching is required to determine the phases within matrix. In this study all samples have been etched with 3% nitale.

Some optical microscope images of the experimental boron added armor steel are given in Fig. 4 according to various applied heat treatments. All microstructures have a martensitic/bainitic characteristic. Some coarse ferrite laths can be found in the microstructures. On the other hand dark colored points refer to very fine precipitates within matrix. As a result of rapid solidification, segregation is formed in the matrix due to enriched interdendritic areas. In general such microstructural formations have negative effects on physical and also mechanical properties of the materials.

Fig. 5a shows segregation regions in experimental steel with the heat treatment of 1000 ºC/1h + 200 ºC/1h. On the image a white network is seen. This network is actually the interdendritic regions where after etching contrast differences appear due to segregation. Interdendritic areas enriched with carbon and alloying elements are hardly etched. In these areas one can find mainly two different phases. One is non-metallic inclusions (in this steel they are MnS which forms due to strong affinity of manganese to sulphur than iron and silicate particles). This inclusion will easily be deformed and can easily form defect sites. Second is blocky type MC carbides that are formed primarily during solidification (Fig. 5b). The image shows in a higher magnification. Once formed these strong carbides do not dissolve during the normally applied austenization temperatures. These kind of coarse undissolved carbides play an important role for nucleation of cracks due to their low bonding to matrix. In general during austenization heat treatment all carbide phases are desired to be dissolved in austenite phase. So, after quenching and tempering adequate amount of fine carbides can precipitate to give optimum mechanical properties to the steel.

Heat Treatments and Mechanical Properties

In this study applied heat treatments consist of austenization, quenching and tempering respectively. Austenization is a kind of heat treatment where in low-alloyed armor steels only austenit (γ) is desired. In this study austenitization is performed only for two temperatures: 1000°C and 1100°C. Austenitization times are ½ and 1 hour. After rapidly quenching of the steel a martensitic/bainitic mix-microstructure is formed. Tempering is applied to obtain a acceptable strength and toughness balance. Tempering is mainly applied for three temperatures: 200°C, 550°C and 600°C. Tempering times are 1, 2 and 3 hours. Table 4 shows applied heat treatments and also mechanical properties of samples after heat treatments. Here are only the results for 200°C and 600°C presented.

Tempering of the samples at 200 °C allows only aging of martensite (martensite-ferrite transformation with almost no secondary hardening precipitates). However a higher temperature such as 600°C is also selected to obtain good toughness results (precipitation of the secondary hardening carbides and their coarsening to some degree). As seen in Table 4, a higher toughness is achieved with tempering at 600 °C / 2h.

Ballistic Performance of Steel

The ballistic test setup is given in Fig. 6. The tests are performed at the company FNSS in Ankara, Turkey. For the evaluation of failure (semi failure or full failure) on the target material through the ballistic tests various plate materials (steel plates with different hardnesses) are subjected to shots with various projectile velocities and the mean value obtained after multiple shots, V_{50}-value, is determined for every plate. In order to compare these values, the plates are classified according to their hardness; 3 pieces of plates (374-418-443 HV hardness) are tested for MIL-A-12560 quality and 1 piece of plate (470 HV hardness) is tested for MIL-A-46100 quality armor steel. For the 3 pieces of plates 7.62 AP shots are done with 0°, that is normal to the plate, for 1 piece of plate 12.7 AP shots are done with 30°. Related results are shown in Fig. 7.

In the ballistic tests performed on 4 plates, results obtained for MIL-A-12560 specification are 32 m/s (100 ft/s) higher than the standart minimum values to be accepted. For MIL-A-46100 specification the only result obtained is 10 m/s (30 ft/s) higher than the standart minimum value. The evaluation of the test results show that all plates fit the acceptance requirements for the MIL-standarts.

Fractographical Examinations

Cleavage is a low-energy fracture that propagates along well-defined low-index crystallographic planes known as cleavage planes. Fig. 8a represents a kind of cleavage rupture in one of examined experimental steel that is heat treated at 1000 ºC/30 min. + 200 ºC/3h. This figure illustrates an example of transgranular rupture and

Fig. 8b illustrates the certain cleavage planes at a high magnification of Fig. 8a. As a result of low temperature tempering, matrix consists of martensite/bainite.

When an overload is the principal cause of fracture, most common structural alloys fail by a process known as microvoid coalescence. The microvoids nucleate at regions such as second-phase particles, inclusions, grain boundries and dislocation pile-ups. As the strain in the material increases, the microvoids grow, coalesce, and finally form a continuous fracture surface. The so called ductile rupture has a characteristic appearence like dimples under SEM. Fig. 9 presents an example of dimple rupture of examined experimental steel from the heat treatment serie of 1000 °C/1h + 600 °C/2h. Depending on increased tempering temperature and time, toughness of the steel increases and this indicates that the plastic deformation capability of the steel increases.

Segregation regions generally are not desired due to their negative effects on mechanical properties of steels. These kind of regions have a low plastic deformation capability similar to grain boundaries and also exhibit a brittle fracture. Fig. 10a illustrates fracture surface of a tensile test sample (heat treatment : 1000 °C/1h + 600 °C/2h) with a tough matrix. The fracture is occured parallel to the rolling direction and in rolling direction elongated MnS inclusions are seen. While interdendritic regions, where elongated MnS is lying have flat surfaces indicating a brittle fracture, dendritic regions have a high toughness and show a ductile fracture with dimples. Fig. 10b represents the transition of a brittle-ductile region in the same sample.

As an example of fractographical examination, the fracture surface of a tensile sample is given in Fig. 11 where the crack propogation is parallel to the rolling direction and in Fig.12 where the crack propogation is normal to the rolling direction. When all fracture surfaces are examined, it is obvious that a desired fracture characteristic of the steel can be obtained with a precipitation strengthened matrix at higher tempering temperatures.

CONCLUSIONS

Quenched and tempered steels consisting of tempered martensitic/bainitic microstructure has a good combination of strength, hardness and toughness and present theirself as an ideal material for an armor steel. Armor steels require an adequate ballistic performance, which is actually a function of mechanical properties of a steel under projectile or blast attacks. As a result, the mechanical properties of the selected material as an armor steel must be developed according to ballistic loadings. Also fractographical observations under statically and dynamically loading are required to understand the ballistic performance of the steel.

In this study, an experimental steel with boron is designed. The newly developed alloy should have adequate heat treatment which would increase the properties of steel. The steel with its moderate carbon amount allows to obtain a sound secondary hardening potential of the matrix. Higher austenitization temperatures and times increases the amount of alloying element solubility in the austenite and hardness (strength) of the newly developed steel is increased. In the case of tempering tempering temperatures also at low tempering temperature (here it is 200 ºC) the hardness is high. But for obtaining a high level of toughness the tempering temperature should be over the secondary hardening maximum (here it is 600 ºC). For the studied austenitization and tempering temperatures and times we obtained different structures where most of them fulfill the requirements for MIL-A-12560 and/or for MIL-A-46100 standarts.

The study of the fracture surfaces completes the view. The ductile fracture attained in the microstructures developes as a function of high toughness and material will resist to impact. On the other hand, high hardness microstructures showing brittle fracture will have lower impact resistance. The experimental steel shows encouraging results of hardness and toughness and with further development work a good armor steel could be developed.

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REFERENCES

[1] Karagöz, Ş., Yılmaz, A., Atapek, H., ‘Development of Quenched & Tempered Steel as Armor Materials Through Alloying and Heat Treatment’, Military Science & Inteligence Magazine, p.42-45, April, (2007).
[2] Atapek, H., ‘Development of an Armor Steel along the Principles of Physical Metallurgy & Its Characterization’, Master Thesis, Kocaeli University, Institute of Applied Science, Turkey, June, (2006).
[3] Sangoy, L., Meunier, Y., Pont, G., ‘Steels for Ballistic Protection’, Isr. Journal of Technology, 24 p. 319-326, (1988).
[4] Crouch I. G., ‘Metallic Armour-from Cast Aluminium Alloys to High Strength Steels’, Materials Forum, 12, p. 31-3, (1988)
[5] Mills, K., Davis, J. R., Destefani, J. D., ‘Fractography’, ASM Handbook, Vol. 12, Materials Park, Ohio/USA, (1987).
[6] Karagöz, Ş., Atapek, H., Yılmaz, A., ‘Development of QT Steels as Armor Materials’, Proc. 4th Iron-Steel Congress, Zonguldak-Turkey, November, (2007).
[7] Karagöz, Ş, Atapek, H., ‘Fracture Behaviour of Armor Steels’, Proc. 8th International Fracture Conference, Istanbul-Turkey, November, (2007).
[8] Karagöz, Ş., Yılmaz, A., Atapek, H., ‘Armor Steels and Their Development’, Proc. 3rd National Defence Technologies Congress, METU, Ankara-Turkey, (2006)
[9] MIL-STD-662F, USA Department of Defence - Test Method Standard, (1997)

TABLES

Table 1. Chemical composition of armor steels.

Alloying Elements	MIL-A-12560 (Mars 190)	MIL-A-46100 (Mars 240)	MIL 46173 (Mars 270)	Mars 300	XH129	Armox 440 T
C	< 0.30	< 0.30	0.37 maks.	0.45-0.55	0.26-0.32	0.21
Mn	1.20	0.95	0.90	0.30-0.70	0.10-0.40	1.20
S	0.005	0.005	0.005	0.005	≤0.01	0.01
P	0.012	0.012	0.012	0.012	≤0.015	0.01
Si	0.2-0.4	0.2-0.4	0.2-0.4	0.6-1.0	0.1-0.4	0.1-0.5
Ni	1.80 max.	1.85 max.	3.00 min	4.5 max.	-	2.5
Cr	1.00	1.6	1.90 max.	0.4 max.	1.0-1.5	1.00
Mo	0.3-0.5	0.5	0.3-0.5	0.3-0.5	0.1-0.5	0.7

Table 2. Mechanical properties of armor steels.

Property	MIL-A-12560 (Mars 190)	MIL-A-46100 (Mars 240)	MIL 46173 (Mars 270)	Mars 300	XH129*		Armox 440 T
Hardness (HB)	277-388	477-534	477-601	578-655	400-450	480-530	420-480
σ_y (MPa)**	1150	≥ 1100	≥ 1100	≥ 1300	1200	1300	≥ 1100
σ_T (MPa)**	1250	≥ 1600	≥ 1700	≥ 2000	1375	1600	≥ 1300-1500
Elongation (%)	≥ 10	≥ 9	≥ 8	≥ 6	10	9	≥ 10
Impact***	60	30 - 40	30	15	16	14	30

* : Two different property group according to heat treatment conditions are given.

** : σ_y = Yield Strength, σ_T = Tensile Strength.

*** : Notched impact (-40 ºC, J/mm^2)

Table 3. Chemical composition of alloy used in experimental study.

Chemical composition, (%-w)									
C	Mn	Si	P	S	Cr	Mo	(Nb+V+Ti)	Co	B
0.25	0.10	0.10	0.016	0.017	1.5	0.5	0.20	4.5	0.03

Table 4. Applied heat treatments on experimental steel and changes on mechanical properties.

Mechanical Properties	Heat Treatments			
	1000°C / ½h + 200°C / 1h	1000°C / 1h + 600°C / 1h	1000°C / 1h + 600°C / 2h	1000°C / 1h + 600°C / 3h
Tensile Strenght (MPa)	1726	1345	1280	1310
Yield Strenght (MPa)	1592	1258	1128	1210
Elongation (%)	8.3	6,9	10.1	6.1
Hardness (HV)	414	385	388	301
Impact Toughness* (J / cm^2)	36.6	52.6	59.0	50.1

*) Tested at room temperature.

FIGURES

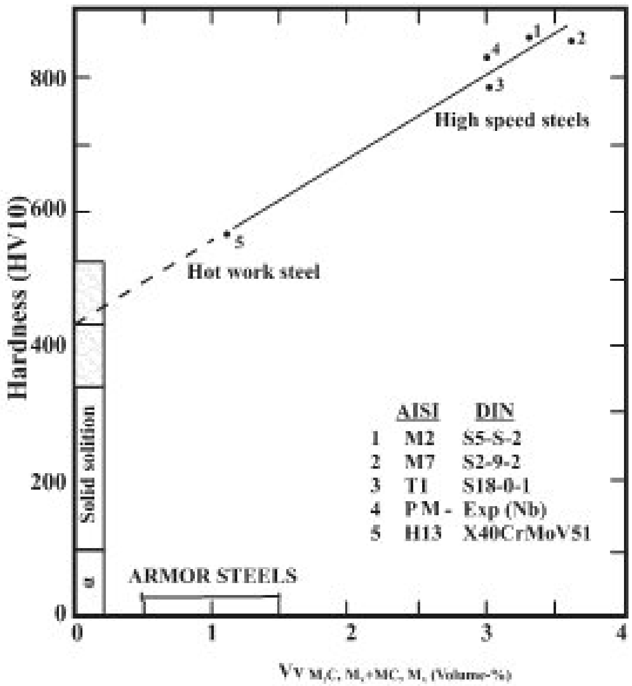


Fig.1. The relationship between the amount of dispersed fine carbides (Vol-%) and matrix hardening potential.

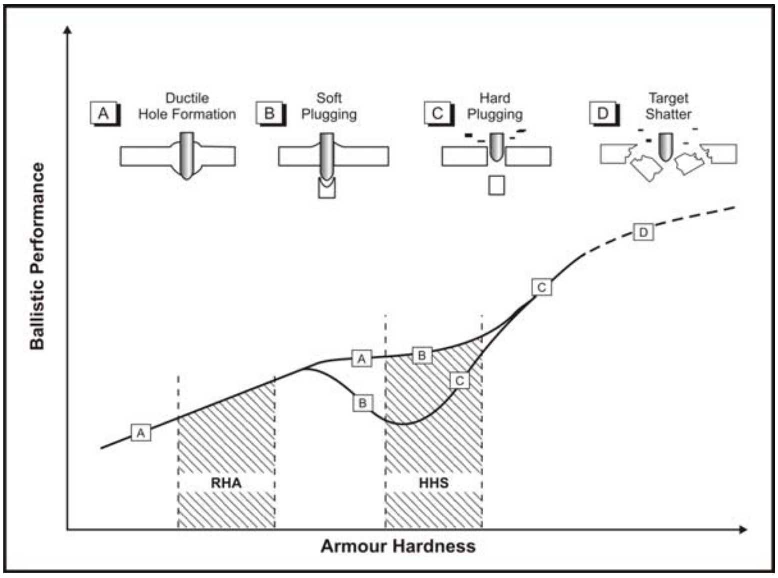


Fig.2. A schematic illustration of the general relationship between target hardness and ballistic performance for the family of armor steel. RHA : Rolled Homogeneous Armors, HHS : High Hardness Steels.

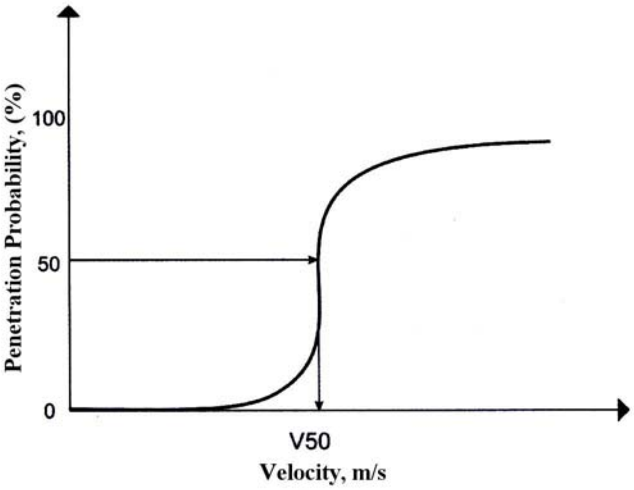
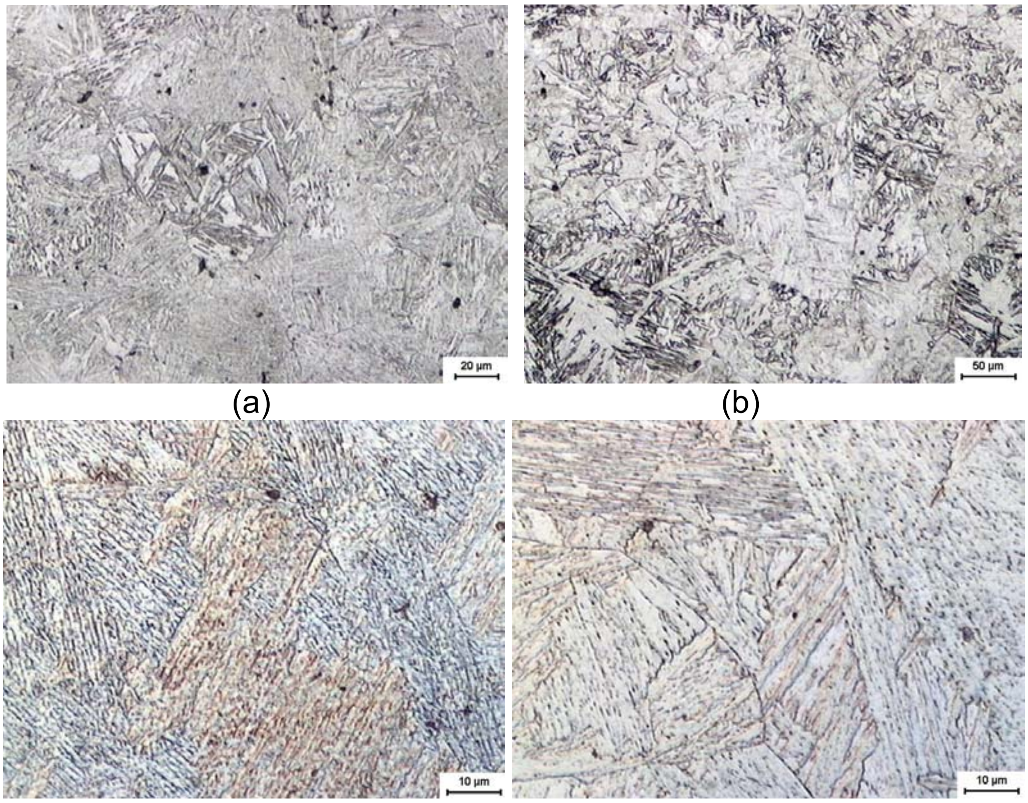


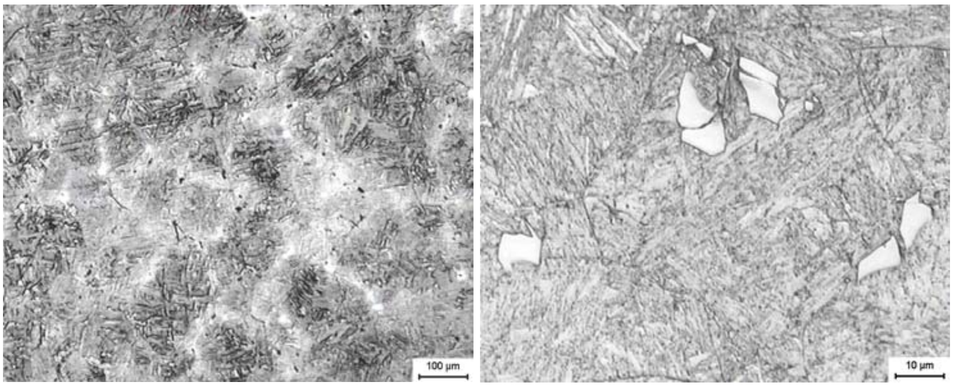
Fig.3. A schematic description of V_{50} velocity.



(a) (b)

(c) (d)

Fig.4. Some optical microscopy microstructure examples of boron added armor steel. Heat treatments : (a) 1000ºC, ½ h / 200 ºC, ½ h (b) 1000ºC, ½ h / 600 ºC, ½ h (c) 1000ºC, 1 h / 200 ºC, 1 h (d) 1000ºC, 1 h / 600 ºC, 1 h.



(a) (b)

Fig.5. (a) An example microstructure for segregation regions.
(b) Undissolved rough carbides during austenization.
Heat treatments : (a) 1000 ºC/1h + 200 ºC/1h, (b) 1100 °C/½ h + 550 °C/3h.

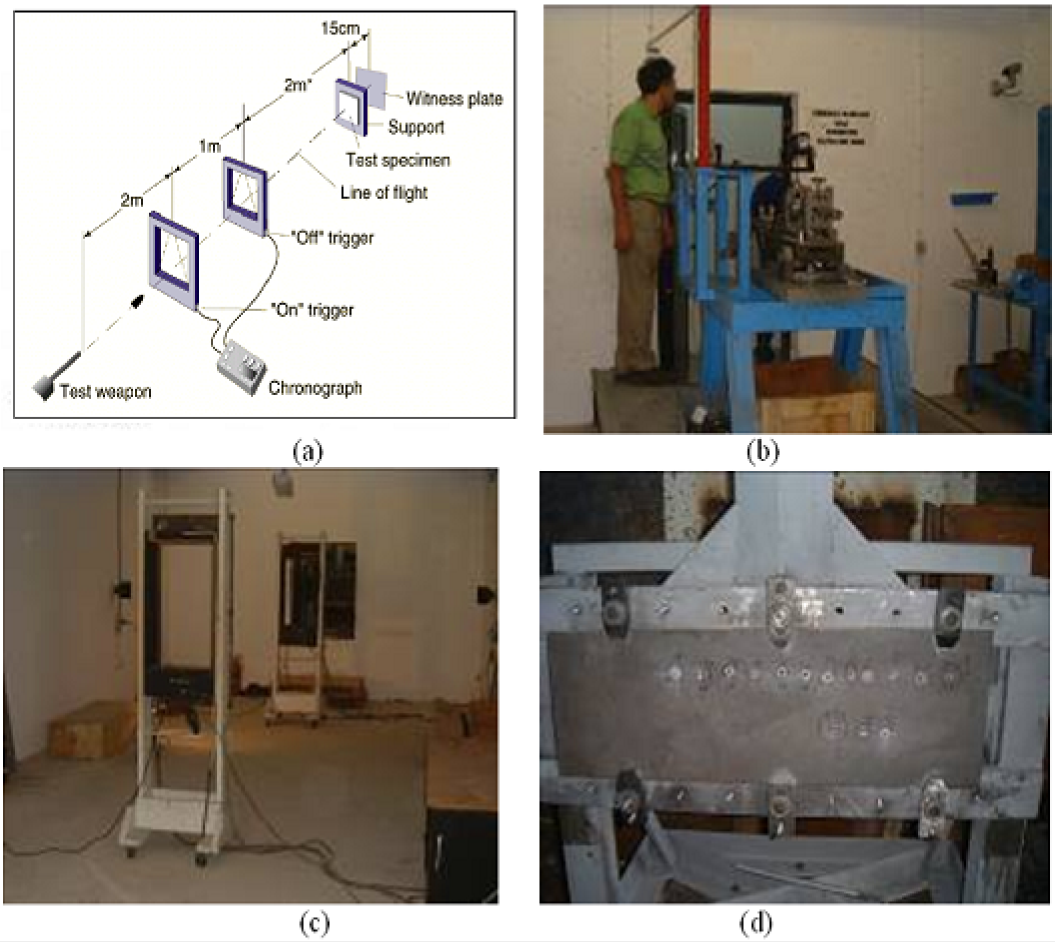
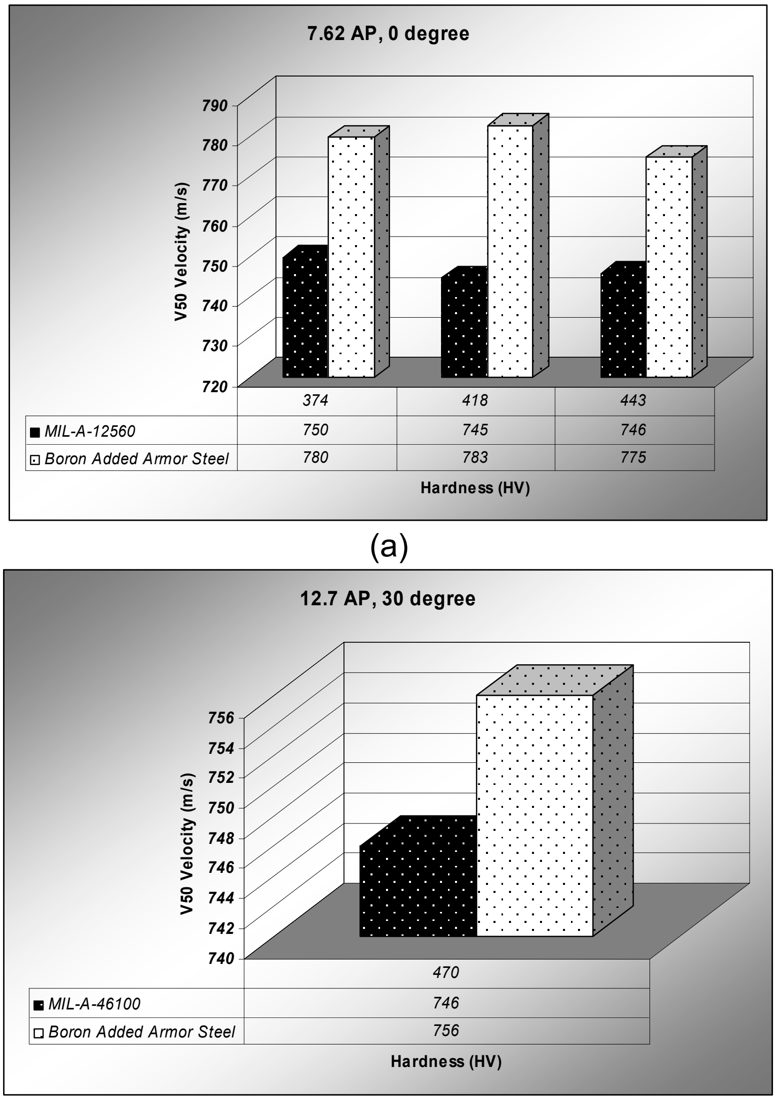


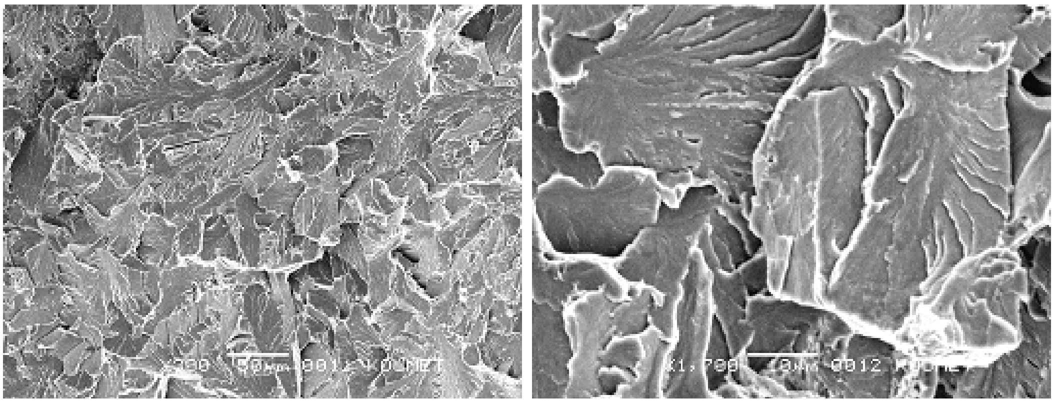
Fig. 6. The ballistic test setup; (a) Design, (b) Test weapon, (c) Velocity measurement, (d) Test plate with some test tracks.



(a)

(b)

Fig.7. A comparison of the ballistic test results between the requirements of MIL-A standart steel and the newly developed boron added armour steel.



(a) (b)

Fig. 8. Fracture surfaces of experimental steel failured by cleavage rupture. Heat treatment : 1000 ºC/½ h + 200 ºC/3h

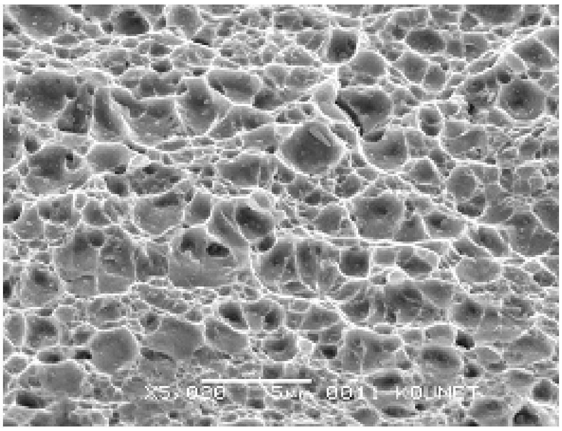
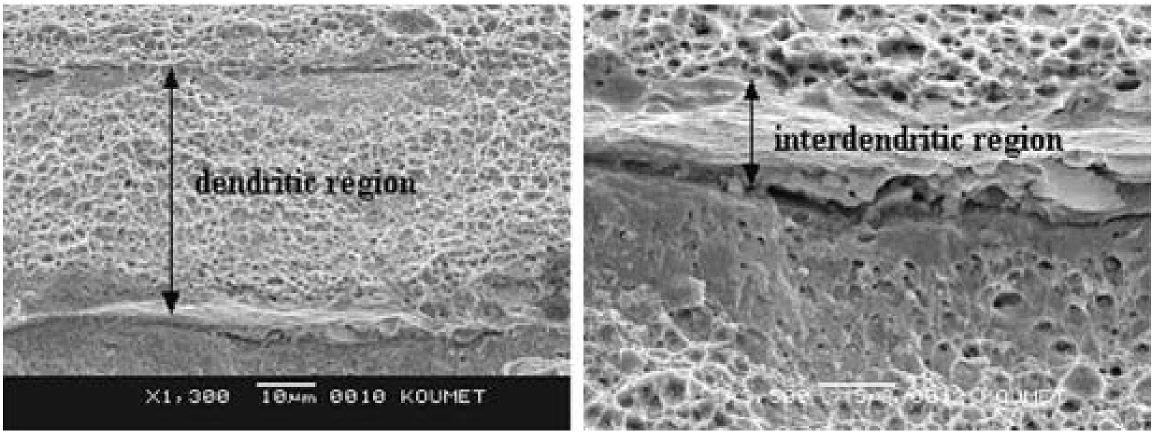
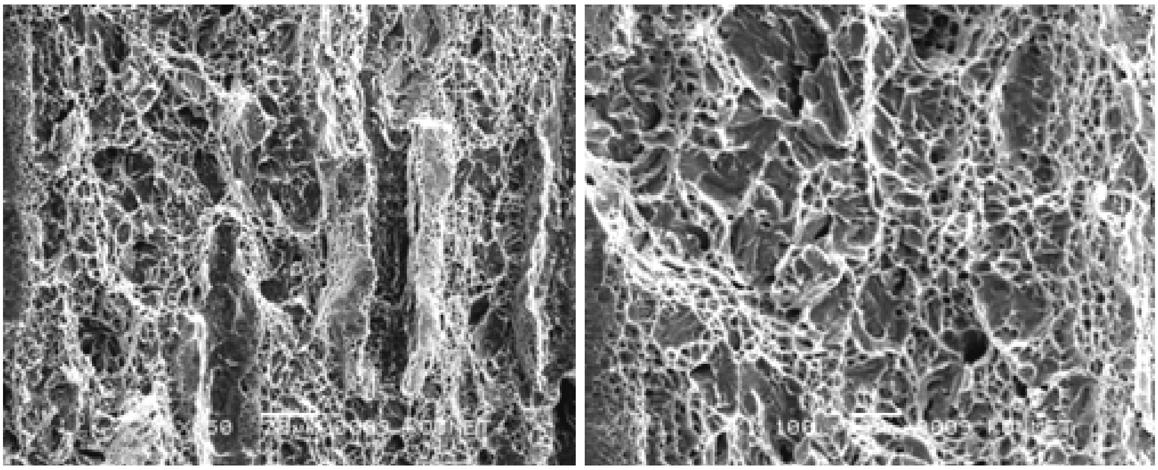


Fig. 9. Fracture surface of experimental steel failured by dimple rupture.
Heat treatment : 1000 °C/1h + 600 °C/2h



(a) (b)

Fig. 10. Fracture surfaces of tensile sample (a) dendritic region within steel, (b) the transition of dendritic region-interdendritic region.
Heat treatment : 1000°C/1h + 600°C/2h.



(a) (b)

Fig.11. Fracture surfaces of tensile tested sample.
Heat treatment : 1000 °C / 1h + 600 °C / 2h

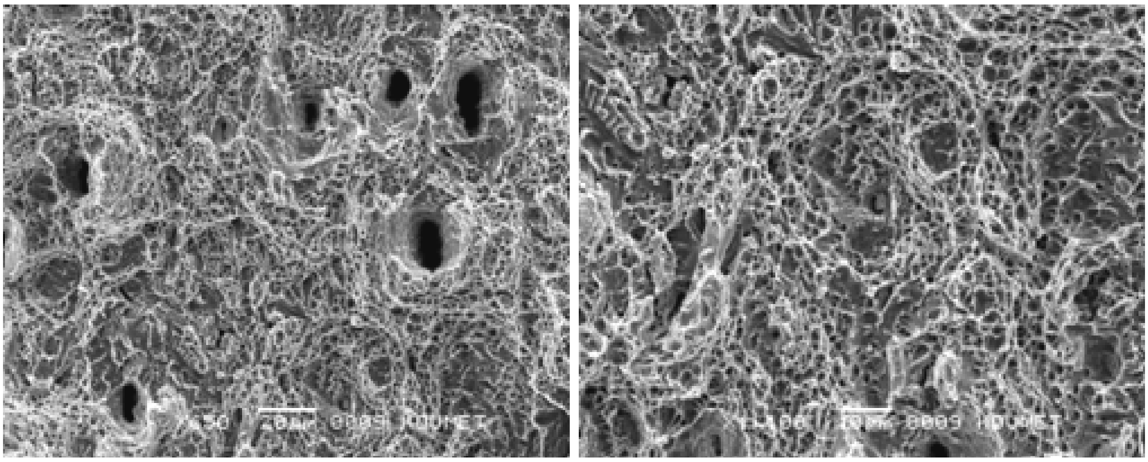

(a) (b)

Fig.12. Fracture surfaces of impact tested sample.
Heat treatment : 1000 °C / 1h + 600 °C / 2h.