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MICROSTRUCTURAL CHARACTERIZATION AND EFFECTS ON MECHANICAL PROPERTIES OF BORON ADDED ARMOR STEELS

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ABSTRACT

The performance of steels depends on the properties associated with their microstructures, that is type, volume fraction, form factor, size and the 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 changes, hot deformation, cold deformation and heat treatment. Each type of microstructure is developed to characteristic property ranges by specific processing routes that control the microstructural changes. Thus processing technologies are used to tailor the final microstructure.

In this study boron added armor steel has been rolled to form sheet product. Austenitization treatment, rapidly quenching and then tempering at various temperatures and times have been performed on the materials respectively. After all of these operations, the phases of the alloy system formed during equilibrium state have been examined and also their amounts are calculated with Thermocalc. Microstructures formed after different heat treatments have been examined by optical microscopy. The effect of formed microstructures on mechanical properties are comparatively given by strength, toughness and elongation values.

KEY WORDS

Armor Steels, Boron Alloying, Microstructure, Heat Treatment, Characterization.

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INTRODUCTION

Armor materials having a specified goal of protection have recently found a wide use as land, air, marine and aerospace applications for civil and military purposes and also as surface material of constructions. The various materials used as armor are listed in Table 1. Recently the heaviest threat on civil and military platforms are bullets with kinetic energy shot from modern firearms. Armor steel mentioned in this study exhibits a high level of ballistic performance against to projectiles as a result of its properties such as high strength, adequate toughness and good weldability [1].

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. This is the reason why the study of perforation mechanisms is required. 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.

Typical armor steels contain carbide forming elements, usually molybdenum and chromium and austenite forming elements, e.g. manganese and nickel. Carbon is added in relation to carbide forming elements. Armored steels primarily used as cast and rolled material are microalloyed with niobium, titanium and vanadium in double combination when subjected to thermomechanical treatment. Table 2 shows the composition of mostly used armor steels in military applications all around the world [2].

Table 3 represents the mechanical properties of armor steels. In this table, series of MIL (USA Armor Quality) are very important for many cases due to their optimal mechanical properties under kinetic and also dynamic impact to armor. On the other hand, XH129 (German Armor Quality) and Armox (Swedish Armor Quality) are known as other armor materials for protection. A comparison for series of MIL is given in Table 4. As seen from this table, the mechanical properties of armor steel differ greatly in as cast and heat treated forms.

Quenched and tempered steels are widely used in automotive, defence, marine industries. These kind of steels have a martensitic/bainitic structure after rapidly quenching. Steel quenching is defined as 'cooling of steel workpieces at a rate faster than in still air'. The cooling rate has to be so fast that austenite should mainly transform within martensite and bainite ranges. In industrial applications, steels are not tough enough after rapidly quenching. So, the usable hardness-toughness balance is obtained during tempering by the selection of time and temperature.

Parameters such as alloy design and the proper heat treatment (quenching and also tempering) are very important to determine the final properties of the product [3]. In this case the optimum mechanical properties, for example high strength, hardness and also toughness, can be obtained by performing a tempering heat treatment within a certain temperature and time range [4-6].

Figure 1 summarizes the mechanism of changes in an iron-carbon martensite structure during tempering at 100-700 °C for 1 hour. In general, after quenching carbon atoms in the martensite structure begin to diffuse and form carbides with iron atoms during

tempering, in the first step $\text{Fe}_{2.4}\text{C}$ and then cementite (Fe_3C), and this is named as cementite precipitation. During this kind of precipitation, the hardness of steel decreases as a result of transformation from martensite to ferrite structure. However various carbide precipitates such as MC, M_2C , M_7C_3 can be formed with addition of some alloying elements that have a strong affinity to carbon at high tempering temperatures. As a result of this, an increase in hardness can be determined which is called as secondary hardness. This characteristic hardness increase is obtained by a complex precipitation hardening.

The precipitation characteristic of some carbides, formed by various alloying elements during tempering is shown in Fig.2. As seen from the figure, the formation temperatures of formed carbides increase with an increase of the carbide stability [7-9].

Secondary hardness precipitates form preferentially upon dislocations and lath boundaries in lath-type martensitic matrix. Maximum value of secondary hardness can be obtained by precipitation of several nanometer sized, semi-coherent, rod shaped M_2C and also several nanometer sized, semi-coherent, disc shaped MC at 540-560 °C. On the other hand Cr-riched M_3C and M_7C_3 precipitates due to Cr form in tempered steels. While the density of M_2C is two times of MC carbides at the initial stage of overtempering and it provides the basics of matrix hardness. This kind of precipitate grows up rapidly and its number decreases depending on its low thermodynamical stability during tempering. This change has been shown with a sample which is a high speed steel tempered at 600 °C in Fig.3. The images have been taken with a field ion microscope where the light spots refer to protruding carbides.

Finally the relationship between the amount of secondary dispersed fine carbides in matrix and their matrix hardening potential has been represented in Fig.4. As it can be seen from the figure, an almost linear relationship exists for several steel based materials [10, 11].

Principally in the armor steel coarse carbides or carbide agglomerates are undesirable due to their toughness decreasing effect. That is why it is expected that carbides dissolve in the matrix at high austenitisation temperatures and precipitate in a fine form as secondary carbides at lower temperatures during tempering. To obtain such a microstructure the steel must be austenitized so that the carbides of the weak and semi-strong carbide forming elements dissolve. At this heat treatment, the material is hold at temperatures 950-1150 °C for a certain time period. After this, a tempering heat treatment follows at temperatures up to 600 °C whereas the carbon and carbide forming elements dissolved in the matrix form fine dispersed secondary carbides in the solid solution and cause an enhancement of hardness and strength.

To obtain a high hardness during tempering it is desired that high amounts of elements like Mo and Cr should dissolve. During solidification of the melt primary MC and secondary M_7C_3 and M_{23}C_6 form. M_7C_3 and M_{23}C_6 carbides go easily into solution at lower austenitisation temperatures, but for MC carbides higher temperatures are needed. Alloying element and carbon level determine the expected theoretical amount of secondary hardening carbides shown in Fig.4 [12].

EXPERIMENTAL STUDY

In this study microstructural changes in a quenched and tempered steel desired to be used as armor steel with a given composition has been investigated by performing different heat treatments. Alloy composition used in the experimental study is listed in Table 5. Chromium and molibdenium have been selected for precipitation hardening and also niobium, vanadium, titanium have been added as microalloying elements. Cobalt is chosen to develop a higher toughness of the matrix. The amount of carbon has been adjusted to a low level for a good weldability. Also boron has been added on 0.03 weight-% level to promote on one side the bainitic transformation, on the other side precipitation of borides/carborides [13].

An armor steel used as armor material is produced primarily by pure casting as well as casting and rolling. Steel has been cast with an AEG medium frequency furnace in 7th Maintenance Center of Turkish Land Forces Command at Tuzla-Istanbul. The steel has solidified in a dendritic form due to solidification rates generally practiced in the ingot metallurgy of the Maintenance Center. Before casting the alloy is kept for approximately 200 s at a temperature range of 60-100 °C above the calculated liquidus temperature. A minimum cooling rate of 1 K/s is maintained until the melt solidified completely. After casting, plates sized 500x550x55 mm have been rolled eleven times and after deformation, sheet steel have been obtained with a size 1500x600x5 mm.

Solidification Modelling by Thermocalc

In this study solidification is examined with Thermocalc. Thermocalc results have been used to determine the solidification sequence and also the amount of formed phases in equilibrium conditions. Table 6 shows the prescribed phases and formed phases in equilibrium conditions for the experimental alloy used in this study. On the other hand Fig.5 represents the relationship between the amount of phase (Vol-%) and temperature for the experimental alloy in equilibrium conditions. In this figure, number 4 curve refers to liquid phase of steel. It is obvious that liquid phase is stable up to 1550 °C. δ -Fe (bcc) is the first solid phase formed when the temperature begins to decrease. In addition to this formation, austenite phase (fcc) forms at a lower temperature as a result of peritectic reaction: liquid + δ \rightarrow γ . Primary M_2B phase forms at approximately 1420 °C and its amount is about 0.4 Vol-%. The amount of primary M_2B phase has no discernible change with decreasing temperature. Eutectic MC carbide phase forms from residual liquid in the interdendritic zones at 1210 °C and its amount is about 0.3 Vol-%. This reaction can be shown as liquid \rightarrow γ + MC. Solid state reactions form after reaching 850 °C and as a result of this reaction ferrite (fcc) forms. Following this formation $M_{23}C_6$ precipitates at 800 °C and its amount is about 4 Vol-%. Also M_7C_3 type carbide phase forms at 700 °C as a solid state reaktion and also its amount is about 0.8 Vol-%. All the transformations are completed almost at 600 °C and the amount of formed phases in Vol-% are given below:

% 94.5 ferrite, % 0.4 M_2B_{primary} , % 0.3 MC_{primary} , % 4 $M_{23}C_{6\text{secondary}}$, % 0.8 $M_7C_{3\text{secondary}}$

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 that results in a single phase (γ) in steels if time and temperature choices are good enough (see Time-Temperature-Austenitization diagram). After rapidly quenching the experimental steel a

martensitic/bainitic microstructure is formed and then tempering is applied to gain an optimum strength and toughness to steel. Table 7 shows applied heat treatments and also mechanical properties of the samples after various heat treatments. Performing of austenization and then quenching, a tempering heat treatment has been applied on samples at 200 °C to provide only aging of martensite (which also diminishes the residual stresses). However also a high tempering temperature such as 600 °C has been selected to gain toughness (and also some secondary hardness) to steel. As shown in Table 7, a higher toughness has been obtained with tempering at 600 °C / 2h. This is a result of dissolved martensite, precipitation of secondary hardness carbides and ripening of these secondary precipitates compared to tempering at 200° C.

Microstructural Characterization

All samples have been prepared by grinding with 320, 600 and 1000 mesh size SiC abrasives respectively and then ground surfaces have been polished with 3µm diamond solution. Etching is required to determine the phases within matrix, and in this study etching is carried out with nitale (% 3 HNO₃) to characterize the microstructure.

For comparison purposes a polished surface of XH129 armor steel is shown in Fig.6. In the matrix elongated MnS type inclusion (Fig.6a) and carbides (Fig.6b) formed in the matrix can be recognised by their different morphology and contrast with optical microscope.

Figure 7 represents the general microstructure of the experimental steel sample after quenching. As seen, steel has a matrix between martensite and bainite according to the cooling rate. Lath-type bainite and lath-type martensite structure can be seen in Fig.7a and 7b.

An example of etched microstructure of XH129 is shown in Fig.8. Microstructure is very homogenous and has a characteristic tempered matrix morphology. On the other hand, some optical microscopy microstructure examples of experimental steel are given in Fig.9 after various heat treatment applications. All microstructures have a bainitic characteristic. Also some coarse ferrite laths can be easily seen. On the other hand dark points refer to very fine precipitates within matrix.

As a result of the alloy content and rapid solidification, segregation can form in the matrix. This formation has negative effects on physical and also mechanical properties of the steels. Fig.10a shows at a low magnification segregation regions in experimental steel, where a heat treatment series of 1000 °C/1h + 200 °C/1h is applied. The interdendritic regions are seen as a network with light contrast because of the hard etchability of these highly alloyed regions. Figure 10b shows at a higher magnification that in the interdendritic region MC carbides are formed due to enrichment of carbon and carbide forming elements; here residual melt allows the formation of 'γ + MC'-eutectic.

CONCLUSIONS

In this study, boron added armor steel is subjected to different heat treatments and the effects of related microstructures on mechanical properties have been investigated. In the first run of experiments, ThermoCalc calculations have been used to determine the

equilibrium solidification sequence of the experimental steel. Type of the phases formed, their temperature range and also their amount have been reported as a function of thermodynamical calculations with ThermoCalc Software. All transformations have been almost completed at 600 °C and finally the amount (Vol-%) of the phases are determined: % 94.5 ferrite, % 0.4 M₂B_{primary}, % 0.3 MC_{primary}, % 4 M₂₃C_{6secondary}, % 0.8 M₇C_{3secondary}.

Austenitization, quenching and tempering have been performed on boron added armor steel respectively. All microstructures after austenitization and quenching are martensitic/bainitic due to rapid cooling. To develop also mechanical properties such as toughness and plastic deformation capability of steel, tempering heat treatment has been performed. With the help of the chosen chemical composition, it is expected that a good balance will exist between toughness and strength due to secondary hardening where Mo and Cr play an important role by forming fine homogeneously distributed carbides within matrix.

On the other hand, undissolved carbides and segregation will give a negative effect on mechanical properties of steel. A high ballistic performance is required for armor steel under projectiles which has a kinetic energy. As a result, a high toughness is required for ballistic protection. Furthermore, as hardness of steel is increased the ballistic performance of steel is also increased. An adequate combination of strength, hardness and also toughness is obtained by heat treatment for the experimental armor steel with the given composition. The results are very encouraging, so further experiments are planned.

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TABLES

Table 1. Armor materials to 7.62* ve 14.5** mm AP (Armor Projectile)

Armor Materials	
<p>Steel *</p> <ul style="list-style-type: none"> - RHA[‡] (HB 380) - High Hardness (HB 550) - Two-times hardened (HB 440-600) 	<p>Glass Reinforced *</p> <ul style="list-style-type: none"> - E glass - S glass
<p>Aluminium *</p> <ul style="list-style-type: none"> - 5083 alloy - 7039 alloy - 2519 alloy 	<p>Ceramics *</p> <ul style="list-style-type: none"> - Aluminium oxide - Aluminium oxide + Al - Boron carbide - Boron carbide + Al - Titanium diboronide
<p>Composites ** (multi layer with ceramic surface)</p> <ul style="list-style-type: none"> - Al + RHA - Steel + RHA - E glass + RHA 	

‡) RHA: Rolled Homogeneous Armor

Table 2. Chemical composition of typical armor steels.

Composition (%)	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	0.3-0.7	0.1-0.4	1.2
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 3. 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

* : given two groups of property according to heat treatment conditions.

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

*** : Notched impact (-40°C, J/mm²)

Table 4. A comparison for series of MIL-A armor steels.

Type of Armor Steel	Hardness (HR _C)	Toughness*	Ballistic Performance**	Alloy Chemistry	Carbon Equivalence
Class I MIL A 12560	34 – 40	21.6	1.00	Mn-Mo-B	0.64
Class II MIL A 12560	29 – 34	28.0	Shock resistance	Mn-Mo-B	0.64
High Hardness Plate MIL A 46100	50 – 53	13.5	1.20	Cr-Ni-Mo	0.85
As cast MIL A 113596	32 – 38	16.3	0.87	Cr-Ni-Mo	0.78

Rectangle plate, thickness of sheet : 25.4 mm, * : tested at -40 °C, J/mm² (transverse)

** : 14.5 mm projectile

Table 5. Chemical composition of the experimental alloy used in this study.

Chemical composition, (Weight-%)									
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 6. Thermocalc calculations data.

Prescribed phases on calculations										
liquid	δ-Fe (bcc)	γ-Fe (fcc)	α-Fe (bcc)	graphite	Fe ₃ C	M ₂ B	MC	M ₂ C	M ₇ C ₃	M ₆ C
Formed phases after calculations										
liquid	δ-Fe (bcc)	γ-Fe (fcc)	α-Fe (bcc)		M ₂ B	MC	M ₇ C ₃	M ₂₃ C ₆		

Table 7. Applied heat treatments on experimental steel and changes of mechanical properties.

Mechanical Properties	Heat Treatment			
	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

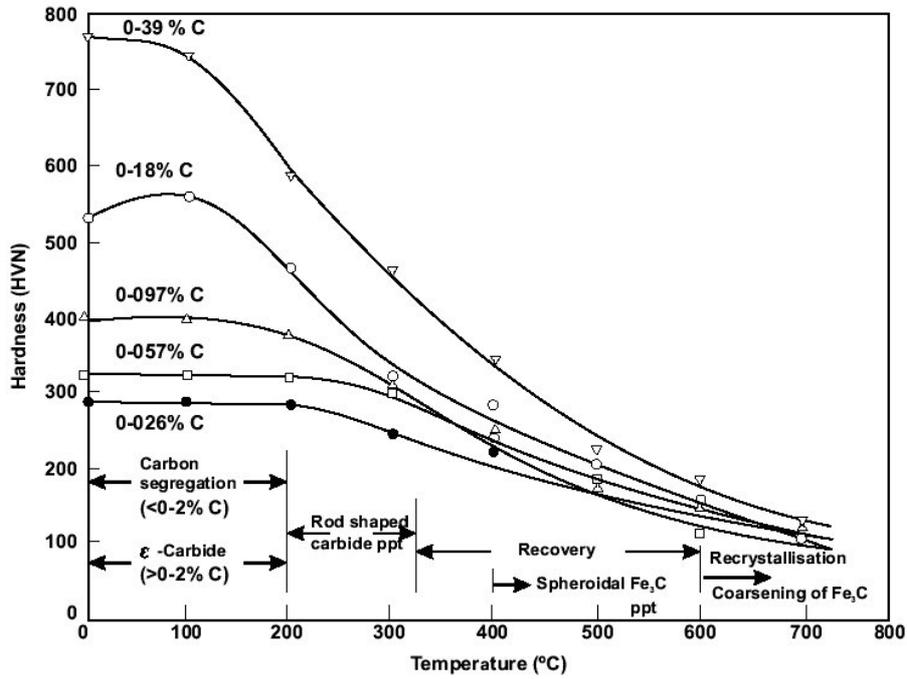


Fig.1. Hardness of iron-carbon martensites tempered 1 hour at 100-700 °C.

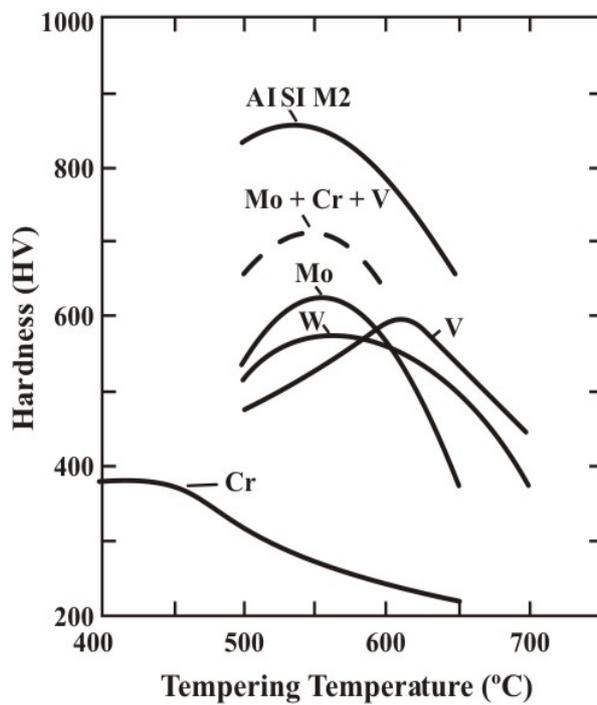


Fig.2. Tempering characteristic of carbides formed by alloying elements.

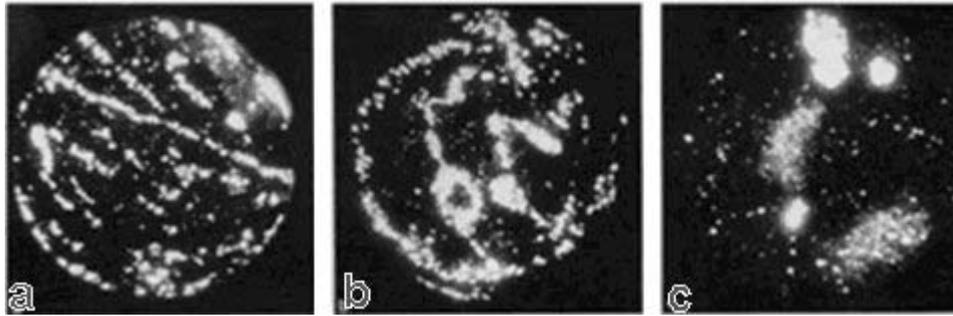


Fig.3. Characterization of typical secondary hardening carbides by using FIM (Field Ion Microscope); coarsening of secondary hardness carbides. Tempering is performed at 600 °C; (a) 100 minutes, (b) 300 minutes, (c) 3000 minutes.

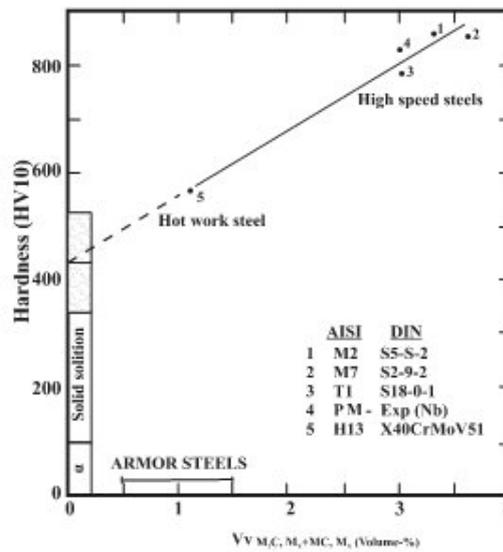


Fig.4. The relationship between the amount of dispersed fine carbides (% volume) and hardening potential of the matrix.

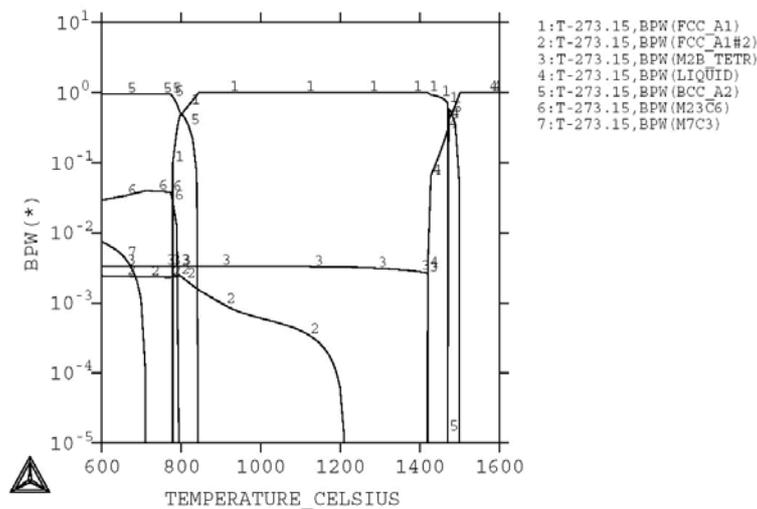


Fig.5. The relationship between the amount of phases formed and temperature for the experimental alloy in equilibrium conditions.

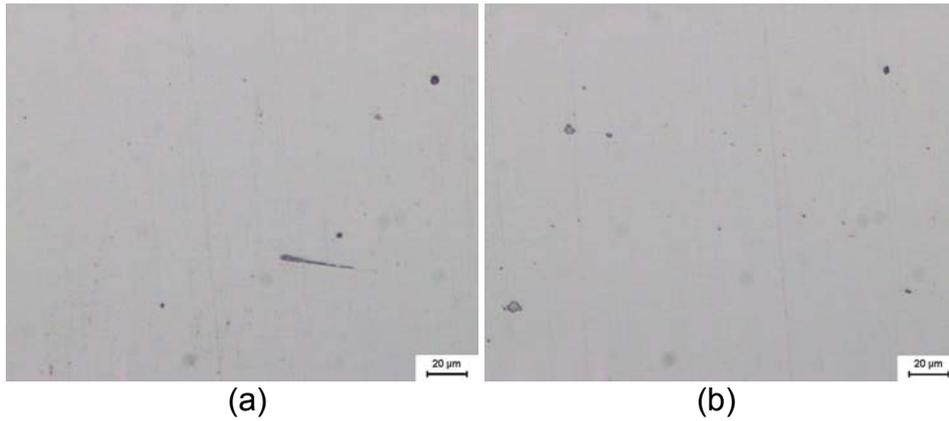


Figure 6. An example for polished surface of XH129 armor steel. (a) deformed MnS (dark grey), (b) carbides (light grey) formed in the matrix.

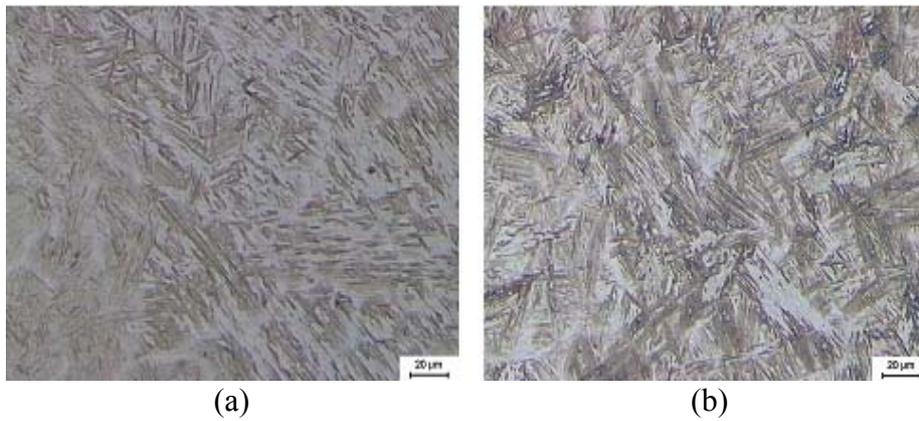


Fig.7. Microstructural examples of experimental steel after quenching. (a) lath-type bainite and martensite, (b) dark grey fields refer to martensite phase. Etched with nitale, OM.



Fig.8. An example microstructure for XH129 armor steel. Microstructure is consisting of homogenous upper bainite.

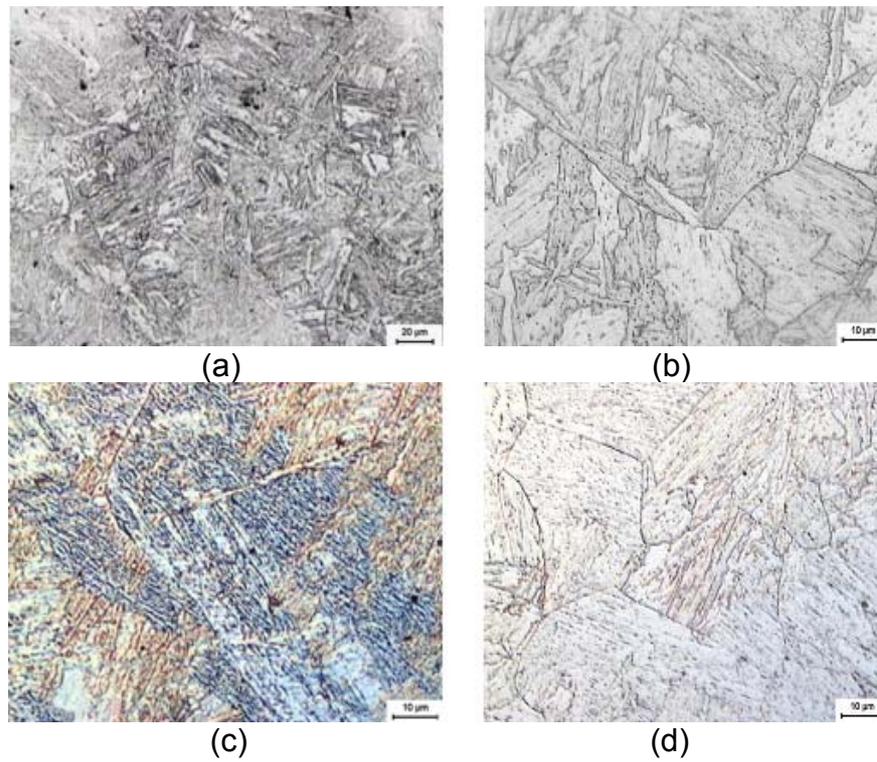


Fig.9. Examples of experimental steel after various heat treatments. (a) 1000°C/½ h+ 200°C/1h, (b) 1000°C/½ h+600°C /1h, (c) 1000°C/1h+200°C/1h, (d) 1000 °C/1h+200°C/1h.

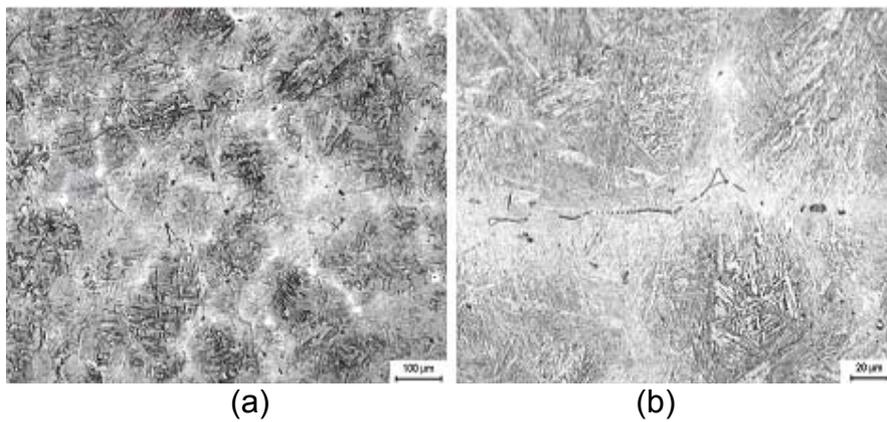


Fig.10. Segregation regions; (a) network of light contrast in the interdendritic regions.(b) during austenization undissolved carbides. Heat treatment :1000 °C / 1h + 200 °C / 1h.