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ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

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RESEARCH ON ARMOR STEEL TECHNOLOGY AND WAYS TO IMPROVE ITS MECHANICAL PROPERTIES

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Abstract. The review article provides an in-depth analysis of armored steel production technologies, highlighting key aspects of production, composition, and the properties of various types of ballistic-resistant materials. The introduction focuses on the comparative characteristics of armor protection materials, with particular emphasis on steel grades such as ARMOX (manufactured by SSAB, Sweden), MARS (ArcelorMittal Industeel, France), RAMOR (Ruukki, Finland), as well as domestic grades like 44C and 56 (Research Institute of Steel, Russia). Special attention is given to the characteristics of each grade and their applications in various fields, such as armor for military vehicles and personal protective equipment. The main part of the article is dedicated to the ballistic requirements set for armored materials in accordance with GOST standards, which regulate the protective characteristics needed to ensure resistance to both bullet impacts and explosive forces. The article also addresses the relevance and necessity of using domestically produced armored steel in Kazakhstan, with a focus on the activities of leading Kazakhstani enterprises such as Kazakhstan Paramount Engineering LLP and Tynys JSC, which specialize in the production of armored vehicles and personal protective equipment. The article also provides detailed coverage of steel melting and casting technologies, exploring various production methods such as the use of open-hearth furnaces, oxygen converters, and electric arc and induction furnaces. The chemical reactions that occur during the melting process and the influence of alloying elements on the properties of steel are also discussed. Additionally, the article examines the thermal and thermomechanical processing of armored steels, including annealing, plastic deformation, quenching, and tempering, and their impact on the formation of structural phases. These processing stages are essential for achieving the desired steel properties, such as hardness, strength, toughness, and ballistic resistance.

Keywords: armor steel, induction furnace, melting, casting, heat treatment, protection class.

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БРОНДЫ БОЛАТТАРДЫ ӨНДІРУ ТЕХНОЛОГИЯСЫН ЖӘНЕ ОЛАРДЫҢ МЕХАНИКАЛЫҚ ҚАСИЕТТЕРІН ЖАҚСАРТУ ЖОЛДАРЫН ЗЕРТТЕУ

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Аннотация. Шолу мақаласы бронды болатты алу технологияларын терең талдауды қамтамасыз етеді, өндірістің маңызды аспектілерін, бронды материалдардың әртүрлі түрлерінің құрамы мен қасиеттерін көрсетеді. Басында броньды қорғаныс материалдарының салыстырмалы сипаттамаларына баса назар аударылады, олардың ішінде ARMOX (ssab өндірісі, Швеция), MARS (ArcelorMittal Industeel, Франция), RAMOR (Ruukki, Финляндия) сияқты болат маркалары, сондай-ақ 44с және 56 (Болат ҒЗИ, Ресей) сияқты отандық сорттар ерекше көзге түседі. Әр брендтің ерекшеліктеріне, оларды әскери техника мен жеке қорғаныс құралдары сияқты әртүрлі нұсқаларда қолдануға баса назар аударылады. Мақаланың негізгі бөлімі оққа да, жарылғыш әсерге де төзімділікті қамтамасыз ету үшін қажетті қорғаныс сипаттамаларын реттейтін ГОСТ сәйкес броньды құралдар үшін белгіленген баллистикалық талаптарға арналған. «Қазақстан Парамаунт Инжиниринг» ЖШС және «Тыныс» АҚ сияқты жетекші қазақстандық кәсіпорындардың қызметіне баса назар аудара отырып, Қазақстанда отандық өндірістің броньды болатынының өзектілігі мен қажеттілігі мәселесі көтеріледі, олар броньды техника мен жеке қорғаныс құралдарының өнімдеріне бағдарланады. Болатты балқыту және құю технологияларына ерекше назар аударылады, өндірістің әртүрлі ерекшеліктері зерттеледі, мысалы, Мартен пештерін, оттегі түрлендіргіштерін, сондай-ақ электр доғасы мен индуктивті пештерді пайдалану. Балқыту процесінде және легирлеуші элементтердің болаттардың қасиеттеріне әсері кезінде жүретін химиялық реакциялар келтірілген. Сондай-ақ, бронды болаттарды термиялық және термомеханикалық өңдеу процестері, мысалы, күйдіру, пластикалық деформация, қатайту, босату және олардың құрылымдық фазалардың пайда болуына әсері қарастырылады. Бұл өңдеу қадамдары қаттылық, беріктік, мықтылық және атуға төзімділік сияқты болат материалының қажетті сипаттамаларына қол жеткізу үшін қажет.

Түйін сөздер: броньды болат, индукциялық пеш, балқыту, құю, термиялық өңдеу, қорғаныс класы.

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ИССЛЕДОВАНИЕ ТЕХНОЛОГИИ ПОЛУЧЕНИЯ БРОНЕВЫХ СТАЛЕЙ И ПУТИ ПОВЫШЕНИЯ ИХ МЕХАНИЧЕСКИХ СВОЙСТВ

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Аннотация. Обзорная статья обеспечивает глубокий анализ технологий получения броневой стали, освещая важные аспекты производства, состав и свойства различных типов бронестойких материалов. В начале делается акцент на сравнительные характеристики броневых защитных материалов, среди которых особенно выделяются такие марки сталей, как ARMOX (производство SSAB, Швеция), MARS (ArcelorMittal Industeel, Франция), RAMOR (Ruukki, Финляндия), а также отечественные сорта, такие как 44С и 56 (НИИ Стали, Россия). Важное внимание уделяется особенностям каждой марки, их применению в различных вариантах, таких как броня для военной техники и средства индивидуальной защиты. Основная часть статьи отведена баллистическим требованиям, установленным для броневых средств в соответствии с ГОСТами, которые регулируют характеристики защиты, необходимые для обеспечения устойчивости как к пульному, так и к взрывному воздействию. Поднимается вопрос актуальности и необходимости использования броневой стали отечественного производства в Казахстане, с акцентом на деятельность ведущих казахстанских предприятий, таких как ТОО «Казахстан Парамаунт Инжиниринг» и АО «Тыныс», которые ориентируются на продукцию бронетехники и средств индивидуальной защиты. Особое внимание уделяется технологиям плавки и литья стали, изучаются различные особенности производства, такие как использование мартеновских печей, кислородных конверторов, а также электродуговых и индуктивных печей. Приведены протекающие химические реакции при процессе плавки и влияния легирующих элементов на свойства сталей. Также рассматриваются процессы термической и термомеханической обработки броневых сталей, такие как отжиг, пластическая деформация, закалка и отпуск, и их влияние на образование структурных фаз. Эти этапы обработки необходимы для достижения требуемых характеристик материала стали, таких как твердость, прочность, ударная вязкость и устойчивость к выстрелам.

Ключевые слова: броневая сталь, индукционная печь, плавка, литье, термическая обработка, класс защиты

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Introduction

At present, the development of armor-resistant material in Kazakhstan with a complex of high physical and mechanical and armor-resistant properties is a promising direction for material engineers. One of the fields of application of armor-resistant material is body armor facilities (BAF) and military equipment armoring. Metal (steel, titanium, aluminum alloys), composite (ultra-high molecular weight polyethylene (UHMWPE), aramid fabric and others) or ceramic (oxide, carbide and mixtures) armor-resistant materials are used as armor in modern BAF and military equipment for protection against destruction means (machine gun and rifle bullets). Among the materials presented, steel-based armor is the most widely used. Steel armor can provide protection up to the 5th level with 11mm thick armor plate, while armor based on ceramics and/or aluminum alloys requires an increase in thickness by 3-4 times (up to 36 and 43 mm). This is evidenced by the protection characteristics of armor materials by thickness and density, which are shown in Table 1 (Yang, et al., 2017: 18-26; Maffeo, et al., 2000: 768-777; Zhao, et al., 2017: 619-625).

Table 1. Specification comparison of materials protection by thickness/density

Type of material	Threat level				
	1	2	3	4	5
Steel alloys	135/1,7	187/2,4	343/4,4	500/6,4	860/11
Titanium alloys	135/3	155/3,5	310/7	445/10	-
Aluminum alloys	135/5	190/7	590/22	860/32	1160/43
Ceramics	-	-	-	380/19	440/36

* in the numerator – density is indicated in g/dm3, in the denominator – thickness is shown in mm

Steel armor is used in almost all means of protection: from individual protection to armoring of military equipment and special transport vehicles. The main task of steel armor is to protect a person from various means of destruction. For this purpose, steel armor shall have all the required properties of strength, hardness, plasticity and toughness to withstand direct hits of bullets fired from small caliber firearms. At the same time, the protective material should not be too heavy, so as not to reduce the speed and maneuverability parameters of vehicles. An important task in the manufacture of armor is to give the metal such properties that it has the ability to evenly distribute the kinetic energy it encounters when hit by a projectile and significantly reduce the point damage, which ultimately preserves the steel from penetrating damages (Madej-Kielbik, et al., 2015: 1800-1808; Kumar, et al., 2020: 5625-5637).

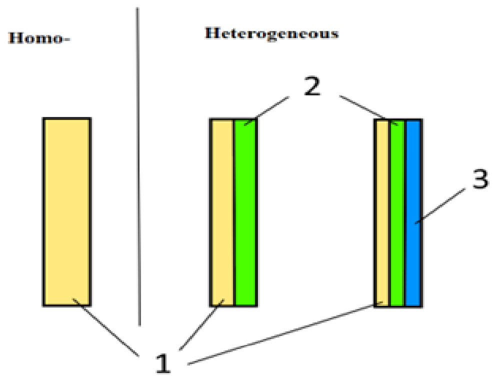
Well-known steel alloys – high quality steels – are used as armor materials. Until now, the following grades of steels have been developed in many countries: ARMOX (SSAB, Sweden), MARS (ArcelorMittal Industeel, France), RAMOR (Ruukki, Finland), 44C and 56 (NII Stali, Russia) and others (Table 2). The presented grades of armor steels have all necessary optimal characteristics and meet modern requirements for armor resistance, strength, hardness, ductility and weight.

One can find the main characteristics of these steel alloys (chemical composition, physical and mechanical properties and their application area) in open sources, but the manufacturing technology (equipment used, melting conditions, heat treatment and deformation, in particular quenching and tempering) is kept in strict secrecy (Yang, et al., 2017: 18-26; Maffeo, et al., 2000: 768-777; Zhao, et al., 2017: 619-625; Wang, et al. 2005: 581-585).

Table 2. Content and properties of some armor steels

Steel grade	Nominal chemical composition	$\sigma_в$, MPa	Hardness, HB
ARMOX 500T	0,32C-0,4Si-1.2Mn-1Cr-1.8Ni-0.7Mo	1750	470-540
ARMOX 560	0,35C-1,0Mn-1,2Cr-3,0Ni-0,65Mo-0,002B	1850	534-601
ARMOX 600	0,43C-0,3Mn-0,25Si-0,5Cr-2,0Ni-0,35Mo	2150	570-640
MARS 270	0,35C-0,75Cr-3,10Ni-0,40Mo	2000	534-601
MARS 300	0,50C-0,80Si-4,0Ni-0,40Mo	2180	578-655
4340 TOD	0,4C-0,3Si-0,6Mn-0,8Cr-1,5Ni-0,2Mo	1900	477-514
RAMOR 550	0,36C-0,7Si-1,5Mn-1,5Cr-2,5Ni	2100	540-600
44C	0,44C-1,1Cr-0,9Ni-0,8Mo	2100	560-610
56	0,50C-3,0Cr-1,7Ni-1,95Mo-0,3V	2300	570-600

Armor steel is divided into two types: homogeneous and heterogeneous. Homogeneous armor has a homogeneous composition of one alloy, while heterogeneous armor has different layer composition. For example, Figure 1 shows a picture of homogeneous and heterogeneous steel armor. The 1st layer is made of hard steel, the 2nd layer is made of medium-strength and -ductility steel, and the 3rd layer consists mainly of ductile steel. The principle of operation of multilayer protection is as follows: upon impact, the hard layer destroys the bullet slug, then the middle layer stops the slug fragments, and after it the plastic layer absorbs the shock wave, distributing the energy over an area (Dong, et al. 2022: 7035-7050; Sorensen, et al. 2008: 1808-1815; Kraus, et al. 2019: 2125).



1 – hard layer; 2 – middle layer; 3 – ductile layer.
Figure 1. Scheme of homogeneous and multilayer heterogeneous protection (Dong et al. 2022: 7035-7050; Sorensen et al. 2008: 1808-1815; Kraus et al. 2019: 2125)

Each armor implies a certain production technology using a wide range of structural materials with the required mechanical properties. In order to obtain homogeneous armor, one needs armor steel with carbon content of 0.25 to 0.4%. This armor has strength of more than 2000 MPa and impact strength of more than 500 kJ/m^2. Heterogeneous armor is obtained from steel through heat treatment or carburizing processes. For heat treatment, higher-carbon steel is used. The carburizing process requires metal with a lower carbon content and alloyed with carbide-forming elements. Thanks to carburization, armored steel obtains the following specifications: strength more than 1600 MPa; impact strength more than 800-1000 kJ/m^2; Brinell hardness more than 9000 MPa (Yang, et al., 2017: 18-26; Maffeo, et al., 2000: 768-777; Dong, et al. 2022: 7035-7050; Sorensen, et al. 2008: 1808-1815; Kraus, et al. 2019: 2125).

Ballistic requirements for BAF and armor equipment are established by the state standards (GOST). For systematization by threat levels there are the following GOSTs: GOST R 50744-95 (2002), GOST R 50744-95 as amended (2014), GOST 34286-2017, GOST R 50963-96, DSTU 4103-2002. For example, Table 1 summarizes main threat levels by resistance against the effect of weapons according to GOST 34286-2017 (Ahmed, et al., 2019: 17-26; Poplawski, et al. 2020: 1-13; Chabera, et al. 2014: 853-859).

Table 1. Main threat levels by resistance against the effect of weapons.

Threat level	Name of weapon	Weapon	Core type	Velocity, m/s
Br 1	9x18mm pistol cartridge with a bullet Pst	9-mm APS	Steel	335
Br 2	9x21mm cartridge with a bullet P	9-mm SR-1	Lead	390
Br 3	9x19mm cartridge with a bullet Pst	9-mm PYa	Steel heat-strengthened	410
Br 4	5,45-39mm cartridge with a PP bullet	5,45-mm automatic weapon AK74	Steel heat-strengthened	895
	7,62x39mm cartridge with a PS bullet	7,62-mm automatic weapon AKM	Steel heat-strengthened	720
Br 5	7,62x54mm cartridge with a PP bullet	7,62-mm rifle SVD	Steel heat-strengthened	830
	7,62x54mm cartridge with a bullet B-32	7,62-mm rifle SVD	Steel heat-strengthened	810
Br 6	12,7x108mm cartridge with a bullet B-32	12,7-mm OSV-95	Steel heat-strengthened	830

In order to meet the protection requirements of the standards and GOSTs, high-strength steels or high-hardness composite multilayered armor are used in modern armored vehicles and tanks. These requirements provide good anti-bullet, ballistic and shellproof protection for armored vehicles up to threat level Br6. However, these requirements do not work with respect to armor-piercing, fin-stabilized, discarding sabot projectile (APFSDS projectile) and other newest means of destruction. This requires modern means of protection: reactive armor, slat armor, active protection systems and others (Chabera, et al. 2014: 853-859; Waseem, et al. 2022: 1-17; Josua, et al. 2022: 261-281).

The development of armor steel technology continues to be relevant for our country, as the produced domestic BAF and military vehicles and equipment need to replace imported expensive armor materials with domestic ones. For example, shells of domestic armored vehicles “Arlan” and “Barys” produced by “Kazakhstan Paramount Engineering” LLP (Astana) are made of ARMOX steel, which is supplied from Sweden. Steel-armored panels of classes Br2-Br4 for body armor produced by “Tynys” JSC (Kokshetau) are also of foreign manufacture. Replacement of materials used for shells of armored vehicles and body armor by the engineered domestic armor-resistant steel alloy is a promising direction in the development of high-hardness steel production not only for military purposes but also for other industries of the country.

Earlier, the present authors in the scientific center of JSC “National Center of Space Research and Technology” (Almaty) for the first time have obtained aluminum-lithium alloy of Al-Mg-Li-Zr system, which is an analogue of grade 1420. The obtained light alloy has all the required performance: armor resistant to shots from AK-74 assault rifle with bullets of 5.45mm caliber with steel core at a distance of 13m. Bullet penetration depth is 13-15mm with plate thickness of 28 mm, compressive strength of 559 MPa, tensile strength of 346 MPa, Brinell hardness of 141 HB, impact resistance of 91 kJ/m^2. The results on aluminum-lithium alloy of Al-Mg-Li-Zr system are given in works. Moreover, engineers of the scientific center JSC “National Center of Space Research and Technology” have developed technologies for obtaining high-strength products from carbon plastic, organic plastic, prepreg (Ablakatov, et al., 2022: 5-14; Ablakatov, et al., 2023: 32-40; Ismailov, et al., 2017: 81-89; Absadykov, et al.,2024: 8-16).

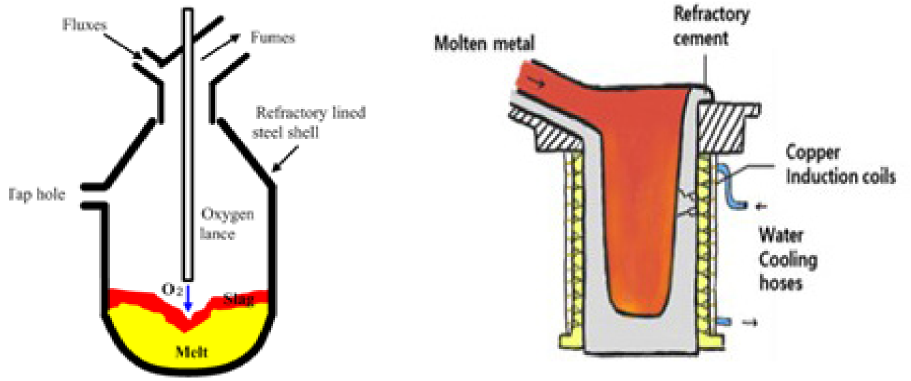
This work will be devoted to the armor steel technology, as well as the study of influence of alloying elements on the properties of steels, running processes and transformations during melting, heat treatment and deformation.

Armor steel technology

Armor steel is produced in the same way as other known high-strength steels. Armored steel properties are achieved by special thermal and thermomechanical treatment, namely deformation, hardening (heating and cooling rate) and tempering (low or high). Steelmaking consists of many complex technological operations and processes: from raw materials preparation for melting and casting to obtaining quality armor steel. The basic technological operation of steelmaking is as follows (Bestera, et al., 2012: 1-5; Muzammil, et al. 2020: 28-38):

- Melting and casting
- Thermal and thermomechanical treatment

Melting and casting. The most common types of steel are produced by melting and casting in open-hearth furnaces, oxygen converters, electric arc furnaces and induction furnaces (Figure 2) (Johaness Schenk, et al., 2015: 1-89; Yulim Choi, et al., 2021: 1121). The open-hearth and oxygen-converter methods as well as electric arc furnaces are mainly used in large industries with a capacity of 10 thousand tons or more, using pig iron, scrap and waste as charge materials. These furnaces can produce traditional steel types. To obtain prime quality high-strength steels, induction furnace is often used, sometimes electric arc furnace (Bestera, et al., 2012: 1-5; Muzammil, et al. 2020: 28-38; Ivica, et al., 2019: 186-196; Showalter, et al., 2008: 2-9).



a) *b)*

Figure 2. Steel melting and casting furnaces. Basic oxygen furnace (s), induction furnace (b) (Johaness Schenk. et al., 2015: 1-89; Yulim Choi et al., 2021: 1121)

Each of these two types of electric furnaces has advantages and disadvantages. Steel smelting in high-frequency, induction furnaces has a number of advantages over arc furnaces. The absence of electrodes will make it possible to obtain steel with low carbon content and low gas content. Induction stirring of metal under alternating currents promotes uniform heating, obtaining a uniform chemical composition and better separation of non-metallic inclusions and gases. These furnaces have high capacity, low losses of alloying elements and high efficiency. At the same time, induction furnaces have a number of disadvantages: they are used for remelting and alloying of pure materials, high cost of lining and equipment, and in industry the capacity is limited from 50 to 4.000 kg, difficulties with desulfurization and dephosphorization (Bestera, et al., 2012: 1-5; Muzammil, et al. 2020: 28-38; Ivica, et al., 2019: 186-196; Showalter, et al., 2008: 2-9; Laura Mustafa, et al., 2024: 1-11).

Steel smelting in induction furnaces is carried out in basic crucibles based on fused periclase (magnesite) or in acid crucibles (liners). Initial substance (charge) for induction furnaces is used with strictly maintained chemical composition of both basic and deleterious elements (mainly phosphorus and sulfur). Various steels with minimum permissible content of impurities and non-metallic inclusions, pure alloys and ferroalloys are used as charge materials. Ferromanganese, ferrosilicon, aluminum and others are added to the liquid alloy to deoxidize the steel. The charge is loaded into the crucible in the following order: steel scrap, refractory ferroalloys are loaded, after melting the low-melting-point alloying materials are introduced, at the end deoxidizing materials are added. In the smelting process, the formed slag is removed from the surface. If necessary, a slag mixture consisting of magnesite powder (10-20%), lime (60-80%) and fluorspar (10-20%) is introduced. After completion, casting of the molten substance into the molds made of refractory material (mainly magnesite) is carried out at a metal temperature of at least 1500°C (Bestera et al., 2012: 1-5; Ivica et al., 2019: 186-196; Showalter et al., 2008: 2-9; David et al., 2011: 65-71; Hakan et al., 2013: 271-277; M.B. Ismailov et al., 2016: 67-71).

During the smelting process, three main reactions take place in liquid-alloy: oxidation period, reduction period and slag formation (Muzammil, et al. 2020: 28-38; Ivica, et al., 2019: 186-196; Showalter, et al., 2008: 2-9; David, et al., 2011: 65-71; Hakan, et al., 2013: 271-277).

Oxidation period:

$$2Fe + O_2 \rightarrow 2FeO$$
$$2Mn + O_2 \rightarrow 2MnO$$
$$Si + O_2 \rightarrow SiO_2$$
$$S + O_2 \rightarrow SO_2$$
$$4P + 5O_2 \rightarrow 2P_2O_5$$

Reduction period:

$$C + 2FeO \rightarrow 2Fe + CO_2$$
$$Si + 2FeO \rightarrow 2Fe + SiO_2$$
$$Mn + 2FeO \rightarrow 2Fe + MnO_2$$
$$2Al + 3FeO \rightarrow 3Fe + Al_2O_3$$
$$Fe/Me + FeO \rightarrow Fe + MeO$$

Slag formation:

$$FeS + CaO \rightarrow FeO + CaS$$
$$3CaO + P_2O_5 \rightarrow Ca_3(PO_4)_2$$
$$CaO + SO_2 \rightarrow CaSO_3$$

Influence of alloying elements and impurities on the properties of steels.

Practically all armored steels have a complex chemical composition. The steel includes not only the basic alloying elements such as carbon, chromium, nickel, molybdenum, silicon, manganese and others, but may also contain phosphorus and sulfur impurities. Interaction of iron with oxygen, nitrogen and hydrogen forms non-metallic inclusions, oxides, nitrides, flakes and other pollutants. Let us consider the influence of alloying elements, impurities and air atmosphere on the properties of steels in more detail (Showalter, et al., 2008: 2-9; David, et al., 2011: 65-71; Hakan, et al., 2013: 271-277; Pradipta, et al., 2020: 1-13).

− Carbon is primarily responsible for steel strength enhancement. As the carbon content increases up to 1.2%, the strength, hardness, cold-shortness threshold, yield strength and electrical resistance increase. At the same time density, thermal conductivity, ductility, viscosity, values of relative elongation and contraction, as well as the value of residual induction decrease. Increasing carbon also reduces deformability and weldability.

− Chromium mainly increases the tensile strength and hardenability of steel, and contributes to a slight increase in its toughness due to the refinement of the austenitic grains. Chromium steels are susceptible to temper brittleness, which can be avoided by their additional alloying with molybdenum.

− Nickel increases the resistance of steel to brittle fracture, ductility and toughness, reduces susceptibility to stress concentrators and provides high resistance to brittle fracture, but the disadvantage of these steels is their high sensitivity to temper embrittlement. As in the case of chromium alloying, this can be avoided by additional molybdenum alloying.

− Molybdenum provide enhanced resistance to austenite grain growth. It is introduced to prevent temper embrittlement. At the same time, molybdenum, while slightly increasing the hardness of ferrite, reduces its impact toughness.

− Silicon, like carbon, hardens steel, increases the strength of steel and reduces its toughness more than other alloying elements. The steel must contain a sufficient amount of silicon, but not reducing the resistance to cracks formation. Silicon is also added purposely into steel for deoxidation. The silicon content as a technological impurity usually does not exceed 0.37%. In steels intended for weld assemblies, the silicon content should not exceed 0.12-0.25%.

− Aluminum (Al) increases the heat resistance and scale resistance of steels. It is also used as an element for the deoxidation of steel during melting or casting.

− Manganese is introduced into steels as a processing additive to increase the degree of deoxidation and eliminate the harmful effects of sulfur. Manganese is considered to be a process-related impurity if its content does not exceed 0.8%. Manganese as a process-related impurity does not significantly affect the properties of steel.

− Sulfur. Sulfur limits as a process-related impurity are 0.035-0.06%. Increase in sulfur content significantly reduces mechanical and physicochemical properties of steels, in particular, ductility, impact toughness and corrosion resistance. During hot deformation of steels and alloys, high sulfur content leads to red-breaking. In addition, high sulfur content reduces the weldability of finished products.

− Phosphorus. Phosphorus limits as a process-related impurity are 0.025-0.045%. Phosphorus, like sulfur, is one of the most harmful impurities in steels and alloys. Increase in its content, even by a fraction of a percent, increasing strength, simultaneously promotes fluidity, brittleness and cold fracture threshold and reduces ductility and toughness. The harmful effects of phosphorus are particularly strong at higher carbon contents.

− Oxygen and nitrogen. Oxygen and nitrogen dissolve in negligible quantities and contaminate the steel with non-metallic inclusions (oxides, nitrides, gas phase).

They have a negative effect on the properties, causing embrittlement and increased cold-shortness threshold, as well as reduce toughness and enduring quality. Oxygen content of more than 0.03% causes steel ageing, and more than 0.1% causes red breaking. Nitrogen increases the strength and hardness of steel but reduces ductility. Increased amounts of nitrogen cause strain aging. Aging develops slowly at room temperature and accelerates when heated to 250°C.

− Hydrogen. An increase in its content in steels and alloys results in embrittlement. In addition, flakes may occur in rolled products, which are induced by hydrogen released into the pores. Flakes initiate the fracture process. Metal with flakes shall not be used in industry.

Heat treatment of armor steel.

The main task of steel heat treatment is to obtain the required equilibrium fine-grained structure by heating to a certain temperature, soaking and cooling. The necessary heat treatment is performed depending on the composition of steel (low-alloyed, medium-alloyed, high-alloyed), on the carbon content in iron according to the diagram of state, deformability, hardenability and other factors. Heat treatment of traditional types of steels is quite well studied and many books and publications describe their methods in greater detail (Showalter et al., 2008: 2-9; David et al., 2011: 65-71; Hakan et al., 2013: 271-277; Pradipta et al., 2020: 1-13; Michael Saleh et al., 2016: 437-442).

Thermal treatment includes annealing, deformation, case hardening, tempering. There are several types of steel annealing: homogenization (diffusion), recrystallization, pre-crystallization, stress relief annealing, annealing of the 1st and 2nd kind, complete, incomplete, isothermal, normalizing and others. Steel hardening involves heating and rapid or slow cooling. Different media are used for quenching: air, water, oil, salt water, nitrogen and other substances that affect the rate of cooling. Tempering is the process of heating the quenched steel, holding it and then cooling it down to form the final structure of the steel. Steel tempering is carried out at low, medium and high temperatures. Low tempering ranges from 150 to 250^{o}C, medium tempering – 350-480^{o}C, high tempering – 500-680^{o}C. There is also thermomechanical processing of steels, which combines plastic deformation and hardening followed by low tempering. Thermomechanical treatment is an effective way to increase the resistance of steel to embrittlement, as it allows to significantly change the structure. The most common technology of steel production in the form of rolled sheet is heating of billets to the temperature of hot deformation, followed by rolling with specified compression and hardening with tempering; in this case heated billets before rolling are subject to hot forging at a temperature of 1100-800°C, isothermal annealing at a temperature of 630-670°C with furnace cooling and reheating for rolling to a temperature of 1050-1100°C in furnace with neutral atmosphere, and after quenching and tempering the billets are subjected to additional tempering, and rolling is carried out at a temperature of 1100-800°C with overall reduction up to 80%. The disadvantage of this method is labor-intensive and complex multi-stage technology with high-energy consumption. Also known is the technology of obtaining high-strength medium-alloy steel by smelting in an electric arc furnace with subsequent slag treatment in a ladle, continuous casting into billets and rolling. The rolled sheet billets are then subjected to heat treatment, including pressure quenching at a pressure of 250 kg/cm^2 with water cooling at a water flow rate of 0.3 m^3/hour and low tempering at a temperature of 150-250°C. Through annealing, deformation, quenching and tempering, the following transformations occur in the steel structure: austenite, pearlite, ferrite, cementite, martensitic, trostitic and sorbitic. The change in steel structure depends on the carbon content of iron. (David, et al., 2011: 65-71; Hakan, et al., 2013: 271-277; Pradipta, et al., 2020: 1-13; Michael Saleh, et al., 2016: 437-442; Kartikeya, et al., 2019: 514-520; Arkadiusz, et al., 2020: 1-13).

Armor steel technology in developed countries, namely their melting and casting conditions, used materials and equipment, heat and thermomechanical treatment conditions are strictly classified and prohibited for publication in open sources. Despite these limitations, based on the above-mentioned methods and methods of obtaining traditional and well-known steels, it is possible not only to improve the basic mechanical properties, but also to obtain armor-resistant steel alloys.

Conclusion

Thus, the results of literature data analysis of armor resistant steels shows as below:

− Strength properties of armor steels are influenced not only by alloying elements, but also by heat treatment conditions: strain hardening, quenching and tempering.

− In order to increase ductility while still maintaining optimum hardness it is necessary to bring the non-equilibrium structure of armor steels closer to the equilibrium martensitic structure by quenching and tempering.

− To increase the strength of armor steels, it is necessary to attempt to obtain a ultrafine-grain structure by strain hardening, saturated with dislocations.

Increase of impact toughness of armor steel occurs at high tempering of around 400-650°C.

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