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ANALYSIS OF PHASE TRANSFORMATIONS IN HEAT-AFFECTED WELDING ZONE OF ALLOYED HIGH-STRENGTH STEELS

Principles of alloying of high-strength quenched-and-tempered steels, used for ballistic protection, as well as the effect of separate alloying elements on quenching and tempering processes for such steels owing to the welding heat action, are analyzed in the article. 15 kinds of steels of various heats, used for manufacturing of armoured fighting vehicles hulls, are selected. For the materials selected the continuous cooling transformation (CCT) phase diagrams are numerically plotted, and phase composition and mechanical properties of metal in weld zone under cooling rate typical for gas metal arc welding (GMAW) process are determined. Based on results of calculated analysis carried out, the materials are determined which do not undergo the softening in all range of cooling rates investigated. [dx.doi.org/10.29010/086.7]

Keywords: alloyed high-strength quenched-and-tempered steels; heat-affected welding zone softening; CALPHAD; thermo-kinetic diagrams; phase composition and hardness of steels.

Introduction

For ballistic and anti-explosive protective facilities, both civil and military application, the high-strength alloyed steels of martensite-bainitic class are used. Ensuring of maximum strength and hardness of rolled sheets of this group steels is achieved by proper scheme of their alloying and thermal processing which consists of quenching and low-temperature tempering.

At present, manufacturing of welded hulls of armoured fighting vehicles (AFV) by enterprises of the Defense-Industrial Complex (DIC) of Ukraine is carried out with utilization of both special armor steels, which are developed and produced according to the proper military normative documentation, and imported foreign protection steels of dual purposes. Feature of the last ones is the specific mode of thermo-mechanic processing immediately in the rolling mill production line and some lesser content of high-expensive alloying elements in comparison with traditional armour steels.

One of the problems of welding of high-strength steels, preliminary thermally processed for maximum hardness, is the impossibility to ensure the equal strength of welded joint. Under action of welding heat the softening of metal in heat-affected zone (HAZ) takes place, which is due to processes of basic metal output structure tempering. At that, the magnitude to which HAZ is soften depends on factors such as weld thermal cycle (heat input) and chemical composition of armorsteels. Because the manufacturers of protection steel rolled sheets of dual purposes are indicate the maximum content of chemical elements only in steel of one or another grade and lower limits are not governed, then the extent of softening of these steels under action of welding heat subjects to the special attention.

In view of the aforesaid, the goal of the present article is the investigation of welding heat effect on phase composition and mechanical properties of high-strength alloyed steels of various alloying schemes.

Characteristic of materials investigated

Chemical composition of steels investigated in the present article is in the Table 1. Materials which are marked arbitrary by «1»...«4» belong to specially developed armor steels. Also the Miilux Protection (M), Quardian (Q), Armstal (A), Armox (A*T), Swebor Armor (S) Protac (P) steels are involved in the analysis, which are protection steels of foreign production and which are used by enterprises of the DIC of Ukraine in welding production of the AFV (number in labeling of these steels characterizes their average Brinell hardness - 500, 560 and 600 HB respectively). The Hardox 500 (H); Toolox 33 (T); Weldox 1300 (W) steels are high-strength wear-resisting and structural steels of foreign production which are delivered also in thermo-strengthening state and may be used for armour protection purposes.

It may be seen that the main alloying elements in the composition of steels investigated are silicon, manganese, chromium, nickel, molybdenum and vanadium; also some of these steels are micro-alloyed with titanium, niobium, boron and zirconium. Taking into

Table 1

Chemical composition of steels investigated, % mass

Steel	Heat No.	Chemical elements																Ref.
		C	Si	Mn	P	S	Cr	Ni	Mo	V	Ti	Cu	Al	Nb	B	Zr	N	
«1»	1	0.236	1.33	1.32	0.016	0.014	0.039	0.037	0.15	-	-	0.058	-	-	-	-	-	[*]
«1»	2	0.29	1.38	1.39	0.022	0.018	0.04	0.11	0.19	-	-	-	-	-	-	-	-	[3]
«2»	1	0.18	1.33	0.45	0.016	0.012	1.35	0.70	0.19	-	-	-	-	-	-	-	-	[4]
«2»	2	0.24	1.37	0.44	0.018	0.015	1.25	0.61	0.20	-	-	-	-	-	-	-	-	[5]
«3»	1	0.37	1.44	0.45	0.009	0.009	0.95	2.37	0.29	-	-	-	-	-	-	-	-	[6]
«4»	1	0.29	1.29	0.64	0.009	0.001	1.63	2.14	0.48	0.187	0.018	0.050	0.028	-	-	-	-	[*]
«4»	2	0.29	0.78	0.69	0.009	0.002	1.73	2.07	0.283	0.198	0.017	0.040	0.040	-	-	-	-	[*]
«4»	3	0.30	1.37	0.77	0.008	0.002	1.68	2.11	0.268	0.220	0.019	0.037	0.036	-	-	-	-	[*]
«4»	4	0.32	1.35	0.76	0.010	0.001	1.88	2.18	0.478	0.206	0.023	0.054	0.040	-	-	-	-	[*]
M500	1	0.26	0.25	1.16	0.008	0.004	0.40	0.17	0.088	0.032	0.041	0.013	-	-	0.0020	-	-	[*]
M500	2	0.273	0.51	1.06	0.007	0.002	0.63	0.40	0.256	0.013	0.025	0.025	0.042	-	0.0020	-	-	[*]
Q500	1	0.253	0.228	0.80	0.012	0.001	0.435	0.84	0.288	-	-	-	-	-	0.0020	-	-	[*]
Q500	2	0.262	0.201	0.809	0.006	0.001	0.541	0.826	0.268	0.003	0.003	0.027	0.043	0.005	0.0021	-	0.0039	[*]
A500	1	0.32	0.21	0.91	0.010	0.006	1.14	1.75	0.36	-	-	0.110	0.026	-	0.0024	-	-	[*]
A500	2	0.28	0.22	0.92	0.010	0.001	0.72	1.07	0.23	-	-	0.140	0.032	-	0.0022	-	-	[*]
A500T	1	0.28	0.26	0.85	0.007	0.001	0.50	0.90	0.35	-	-	-	0.051	-	0.0020	-	-	[*]
A560T	1	0.35	0.27	0.84	0.007	0.001	0.49	1.44	0.45	-	-	0.190	0.053	-	0.0020	-	-	[7]
A600T	1	0.40	0.25	0.70	0.009	0.001	0.50	2.03	0.353	-	-	0.020	-	-	0.0020	-	-	[*]
S560	1	0.33	0.26	1.32	0.010	0.001	0.40	0.06	0.02	0.010	0.04	0.030	0.046	0.001	0.0027	-	0.0040	[*]
P500	1	0.27	1.07	0.706	0.009	0.001	0.637	1.094	0.296	0.039	-	0.276	0.054	-	-	-	-	[8]
H500	1	0.25	0.26	0.69	0.010	0.001	0.57	0.06	0.16	-	-	-	-	-	0.0010	-	-	[*]
T33	1	0.22	1.07	0.79	0.008	0.001	1.04	0.06	0.19	0.098	0.014	0.010	0.013	0.017	0.0020	-	0.0030	[9]
W1300	1	0.21	0.21	0.85	0.008	0.002	0.47	1.26	0.39	0.021	0.003	0.020	0.006	0.015	0.0010	0.002	0.0038	[10]

[*] – certificates of rolled sheets manufacturer

account the carbon content 0.20...0.40 %, after proper thermo-mechanical processing the rolled sheets from these materials have martensite or martensite-bainitic structure, which, together with jointly used technologies of grain refining, provide necessary level of operating characteristics for it. At the same time, different content of above-mentioned elements in composition of the steels investigated stipulates the differences in character of metal softening of welding HAZ of these materials [1, 2].

Owing to high coefficients of dimensional discrepancy with iron atoms, manganese and nickel strengthen effectively the ferrite solid solution. Because such effect requires relatively slow cooling from austenization temperature, it is widely used in air-hardened steels. Addition of manganese and nickel to the quenched-and-tempered steels investigated provides the increase of resistance of supercooled austenite and thus increases their quenching ability. At that, 1 % of manganese acts as 4 % of nickel [11—13].

Disadvantage of manganese is its ability to increase considerably the austenite grain under heating up to high temperatures. As a result, the content of manganese, as an alloying element, in steels investigated was limited approximately to 1.5 %.

Nickel reduces the ability to the brittle rupture and increases the ductile properties of steels. Nevertheless, its addition to the composition of armor steels in a quantity more than 3 % is undesirable, because in such case their properties became supersensitive regarding the composition variations [13].

Silicon retards the cementite formation at the low-tempering temperatures of 200...350 °C, which promotes the increasing of the steel tempering ability and ε-carbides stabilization [11, 14, 15]. Moreover, it more effective strengthens the ferrite solid solution in comparison with nickel [13]. Nevertheless, owing to nonmetal inclusions formation, stipulated by silicon quantity increase, the tendency towards decarbonization and overageing during heating, require limitation of its content in steels at the level 1.2...1.5 %.

Chromium, molybdenum and vanadium are carbide-forming elements which increase the tempering resistance of steels investigated (including also the welding heat action) at the expense of secondary hardening effect caused by carbides formation. Introduction of chromium into steel in quantity of 1.2...2.5 % increases its quenching and reduces in a small extent only the temperature of martensite transformation [13]. Nevertheless, secondary hardening owing Cr_7C_3 carbides formation during heating approximately up to 500 °C reduces noticeably the steel quenching in case of its additional alloying only with other carbide-forming elements (molybdenum, vanadium, niobium) [16].

Molybdenum, which is presented in compositions of all steels investigated (see the Table 1), effectively reduces the carbon diffusion in -solid solution, as well as provides, as a carbide-forming element, the secondary peak hardening by tempering at the temperature about 550 °C [17]. The mechanism of secondary hardening effect under condition of high temperature tempering is in formation of highly dispersed Mo_2C phase due to limited molybdenum solubility in cementite.

Role of vanadium in alloying of quenched-and-tempered steels in general is similar to molybdenum. It ensures the steel secondary hardening by V(C, N) particles which precipitate from solid solution at the temperature about 600 °C [11, 18]. Besides, vanadium delays the pearlitic transformation and, at the expense of austenite stabilization, reduces the temperature of martensite and bainitic transformations [12].

Most essentially the effect of carbide-forming elements on properties of armor steels is revealed during complex alloying. Chromium and molybdenum, which are transformed into austenite during heating for quenching, ensures high quenching of steel, and vanadium carbides, dissolved incompletely during the heating, limit the grain growth and promote the obtaining of final fine-grain structure [18].

According to [19], sharp increase of chromium steels quenching ability upon the molybdenum addition in its composition takes place mainly owing to chromium displacement by molybdenum out of carbide phase. Displaced chromium atoms transfer to the solid solution and increase additionally the supercooled austenite stability.

Niobium, which also is a carbide-forming factor, is used as a microalloying element for obtaining of fine-grain structure of rolled steel, because its carbides are dissolved entirely at the temperatures essentially higher than A_{c3} temperature only. According to [16] data, intensive grain growing in steels with niobium began at the temperatures above 1150 °C.

Role of titanium and zirconium micro-additives also is in the grain refinement. Carbides and carbonitrides of these elements, formed during heating up to the quenching temperature, limit the austenite grain growth [14, 16].

Microalloying of some of the steels investigated with boron increases essentially their quenching ability and promote the grain refinement [20, 21]. According to [20], effect of 0.002 % of boron addition on steel quenching rise is equivalent to addition of 0.2 % of molybdenum or 1 % of nickel. Therefore, the microalloying with boron, which permits to save the critical alloying elements, is widely used for manufacturing of high-strength steel rolled sheets, which are subject to quenching and tempering. Effect of boron is in delay of austenite disintegration owing to its ability to precipitate along boundaries of the primary grain [22]. Because the boron influence on austenite transformation kinetics increases at the high cooling rates [21], the microalloying by this element are most widely used for such steels which are subjected to high-speed quenching.

According to conclusions of the analysis carried out, the role of alloying elements in composition of quenched-and-tempered steels for ballistic protection is presented in the Table 2.

Table 2

Principle of alloying of quenched and tempered steels for ballistic protection

Alloying element	Estimated effect on technological properties of steel
Mn	- raises steel quenching ability - strengthens ferrite solid solution
Ni	- raises steel quenching ability - strengthens ferrite solid solution - reduces tendency to brittle rupture - rises ductility and impact viscosity
Si	- reduces martensite disintegration at low tempering temperatures - strengthens ferrite solid solution
Cr	- ensures secondary hardening at approx. 500 °C - raises steel quenching ability
Mo	- reduces martensite disintegration upon heating - ensures secondary hardening at approx. 550 °C - raises steel quenching ability
V	- ensures secondary hardening at approx. 600 °C - limits austenite grain growth - raises steel quenching ability
Nb, Ti, Zr	- limit austenite grain growth
B	- raises steel quenching ability - limits austenite grain growth

Procedure of investigations

In order to evaluate the effect of chemical composition of steels investigated on structure and properties of the HAZ metal, the JMatPro software package was used. Its work is based on utilization of method of thermodynamic calculation of equilibrium state of the CALPHAD (CALculationofPHAseDiagrams) system [23]. The program permits to fulfill on base of alloy chemical composition and parameters of its thermal processing (including welding thermal conditions) the computing experiment and forecasting of phase structure, phases chemical composition and their mass part at the different temperatures. Further simulation of physical and mechanical properties of the material is carried out on base of multistage calculating algorithm which provides the determination of the extent of effect of each alloying element or impurity on properties of separate phases, calculation of properties of each phase, data superposition for separate phases, and calculation of properties already for all multicomponent system by the rules for mixtures, as well as by physical laws, which establish the connection between separate properties.

The main output data, which is necessary to input by the JMatPro user to obtain necessary properties of the material, are its correct chemical composition and index, which characterizes the size of its grain in final state (grain grade or average size). On the base of these data the JMatPro forecasts wide spectrum of properties beginning from diagrams of supercooled austenite transformation up to structure diagram of metal of the heat-affected welding zone (HAZ) and curves of strain hardening in wide range of temperatures and strain rates.

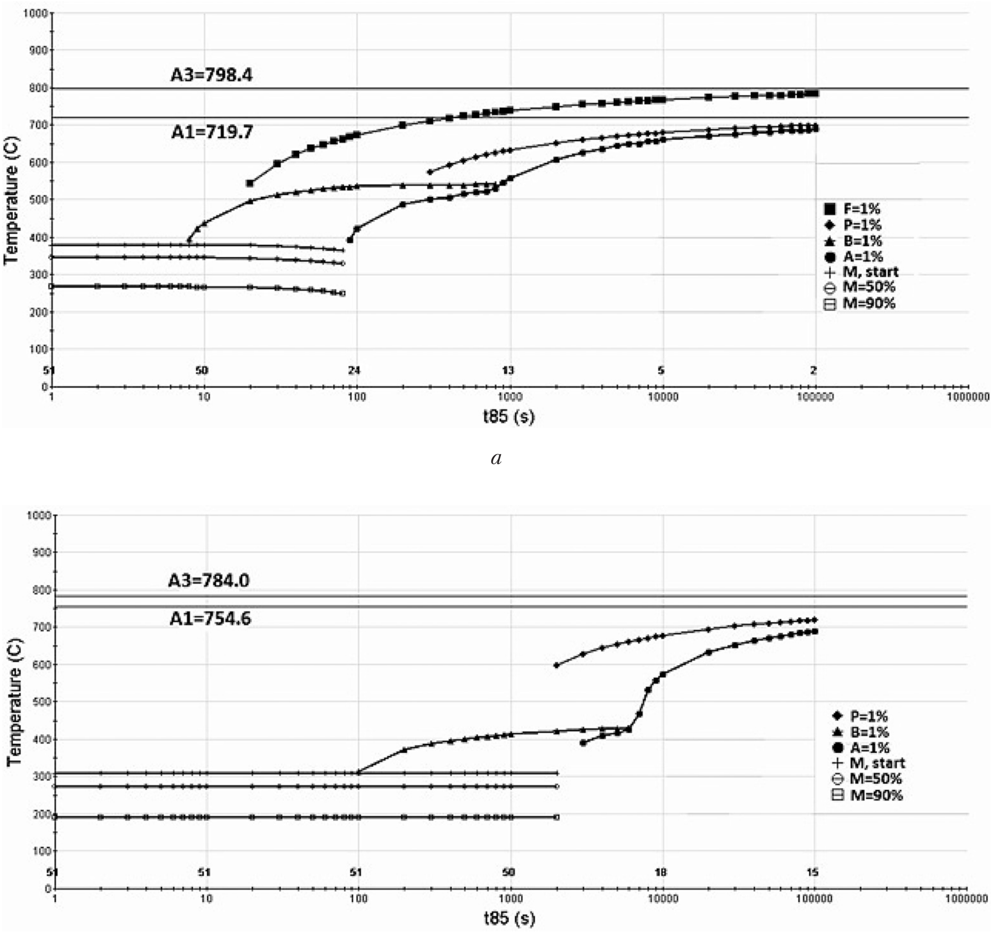
Used in the JMatPro program calculation algorithm for diagrams of austenite isothermic transformation is based upon utilization of calculating models of J.S. Kirkaldy, H. K. D. H. Bhadeshia та J. L. Lee [24—27]. After isothermic diagrams plotting their reconstruction is carried into diagrams of supercooled austenite decay while continuous cooling according to the additivity rules stated in articles [24, 26, 28]. Kinetics of martensite transformation is calculated according to parametric equation from K. W. Andrews [29], supplemented with thermodynamic model presented in [30].

Method of calculation of steels physical properties [31, 32] envisages, first of all, determination of properties of each phase of multi-component systems separately with utilization of simple model of binary solutions. After that the corresponding physical properties (heat capacity, heat conductivity, thermal expansion coefficient, Young modulus, Poisson modulus, etc.) are calculated already for the alloy in whole, using the model of multi-component mixture [33].

Algorithm of the materials mechanical properties calculations in the JMatPro, which takes into consideration interconnection between grain size and yield strength according to the Hall-Petch law, is presented in [31].

Results of calculation

According to chemical composition of each heat of steel investigated (see the Table 1), the CCT-diagrams were plotted numerically. As an example, in the Fig. 1 the diagrams for M500 steel (heat No. 1) and «4» steel (heat No. 1) are presented. Average size of austenite grain, necessary for calculations, was selected according to article [34] and was equal to 10 μm. It may be seen that more higher content of carbon and other elements, which increases the quenching ability, in com-



a

b

Fig. 1. Calculated in the JMatPro CCT-diagrams for steels:
a — M500 (heat No. 1) and *b* — «4» (heat No. 1)

position of «4» steel, results in lower temperature of martensite transformation beginning and more wide range of cooling time values in critical temperature band 800...500 °C, which determines exclusively the matrensite structure of this steel in comparison with M500 steel.

Taking into account the constructional peculiarities of AFV welded hulls and used for its manufacturing GMAW process, the range of cooling rates of HAZ metal in critical temperature interval of austenite disintegration is usually about 5...30 °C/s. Taking into account the above-mentioned, it was calculated for all steels investigated the mechanical properties and phase composition of HAZ area metal, which heats up while welding to the temperature of 1250 °C and cools with average rate 5, 10, 15, 20, 25 and 30 °C/s. Summary results of calculations for «4» steel (heat No. 1) and M500 steel (heat No. 1) are in the Table 3.

It should be note that according to requirements of normative document of MoD of the USA MIL-DTL-46100 "Specification for delivery of armor plate, steel, wrought, high-hardness», for ensuring of necessary anti-bullet protection, the hardness of rolled sheets of these steels should be not less than 48 HRC, which responds to minimum values of yield strength 1250 MPa and tensile strength 1450 MPa. From the Table No. 3 it may be seen that according to calculation data for «4» steel this requirement is satisfied in all range of cooling rates investigated for heat-affected welding zone, in spite of M500 steel.

Summary analysis of quenching ability of steels investigated on the base of results of CCT-diagrams plotted is presented in Fig. 2. The more is maximum time of steel cooling in inter-critical temperature interval 800...500 °C, which secures solely martensite final structure, the higher is resistance of supercooled austenite and quenching ability of the steel considered.

In Fig. 3 and 4 the influence of average rate of HAZ metal cooling of steels investigated (see the Table 1) on martensite final content in it and its final hardness are presented. It may be seen, that these dependences are directly proportional. At that, «4» steel of all heats investigated, as well as Armox600T and Armstal 500 (heat No. 1) steels, demonstrate the calculated hardness of heat-affected zone at the level of MIL-DTL-46100 requirements, independently of cooling rate.

Table 3

Phase composition and mechanical properties of weld zone metal of steels investigated

Steel	«4» (Heat No. 1)						M500 (Heat No. 1)					
Cooling rate, °C/s	5	10	15	20	25	30	5	10	15	20	25	30
Phase composition, % mass (M/B/F)*	100/0/0	100/0/0	100/0/0	100/0/0	100/0/0	100/0/0	0/80/20	33/57/10	63/31/6	80/16/4	89/9/2	93/5/2
Hardness, HRC	49	49	49	49	49	49	25	38	45	48	49	49
Tensile strength, MPa	1571	1571	1571	1571	1571	1571	865	1177	1403	1523	1570	1593
Yield strength, MPa	1329	1329	1329	1329	1329	1329	622	917	1149	1277	1329	1353

*M — martensite; B — bainite; F — ferrite

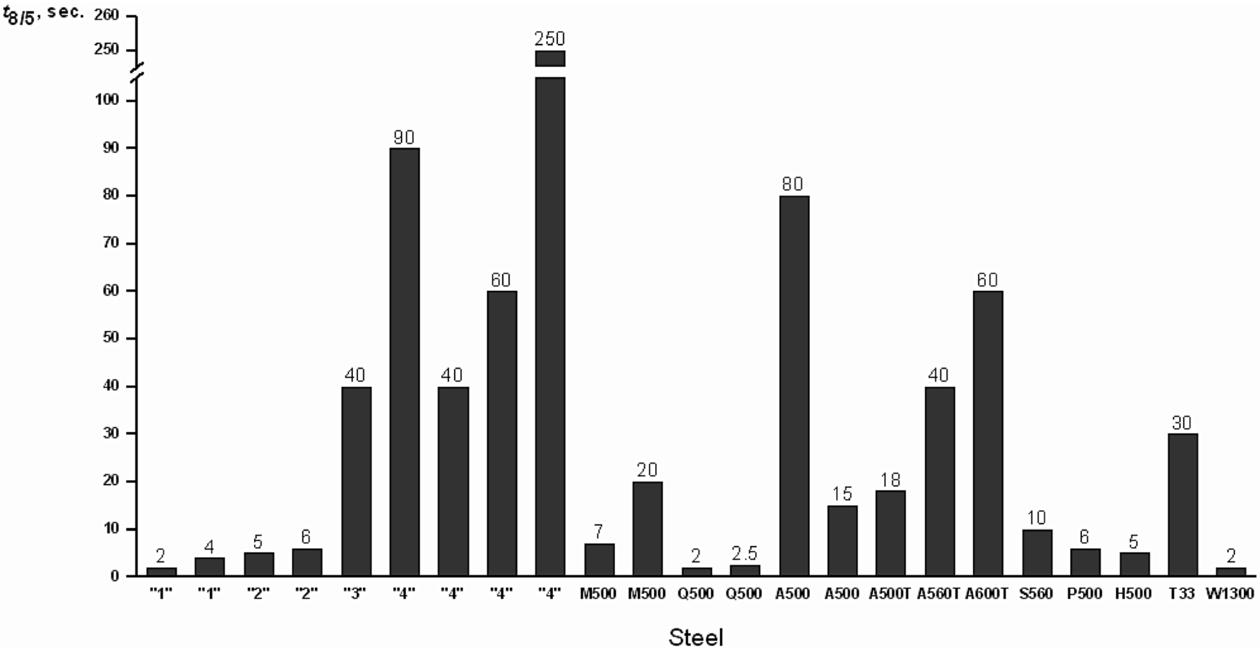


Fig. 2. Maximum time of cooling in temperature range 800...500 °C, which secures solely martensite final structure of steels investigated

Also, negligible cooling rate sensitivity demonstrates Toolox 33 steel and «2» steel (heat No. 2). At the same time, for «2» steel with lesser carbon content (heat No. 1) the achievement of hardness of heat-affected zone about 48 HRC is not succeeded at any of cooling rates investigated, as for low-carbon heat No. 1 of «1» steel. Quardian 500 steels of both heats investigated in the present article, as well as Protac 500 and Weldox 1300 steels, demonstrated minimum ability to afterhardening from the temperature 1400 °C and thus they are softened under welding conditions most of all. Other investigated steels under welding heat action should have required by standards hardness and martensite structure at cooling rates 10...25 °C/s depending of their alloying.

Conclusions

Operating characteristics of welded items manufactured from ballistic protection steels investigated depends on HAZ metal hardness, which, in turn, depends directly on martensite phase quantity in it. By results of numerical simulation of phase transformations and mechanical properties of welding HAZ metal of 15 steels of different heats investigated, they may be divided conditionally by three groups:

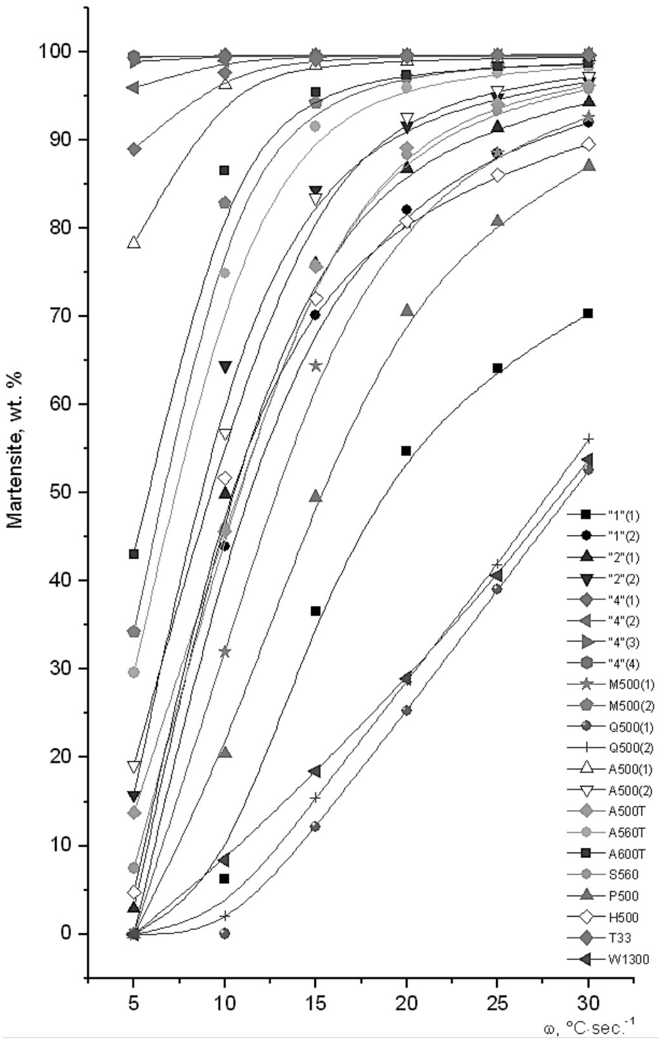


Fig 3. Influence of average cooling rate on final martensite content in metal of heat-affected welding zone of steels investigated

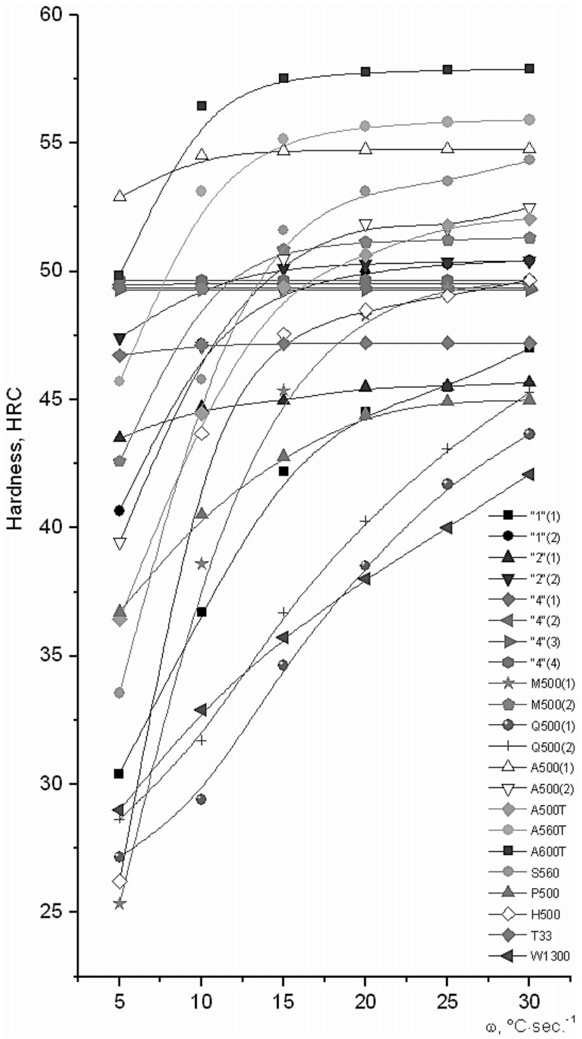


Fig. 4. Influence of average cooling rate on final hardness of heat-affected welding zone metal of steels investigated

1. Steels, which are not soften due to welding heat affection in all cooling rates range 5...30 °C/s. Ultimate hardness of metal of weld zone of these steels is not decent lower than 48 HRC. To this group may be attributed «4» steel of all heats investigated and Armox 600T steel.

2. Steels with limited tendency to afterhardening in condition of welding thermal cycle action. Necessary hardness level of weld zone metal for these steels is ensured at the cooling rates 10...25 °C/s, depending of their alloying. To this group may be attributed «1» and «2», Armox 500T and 560T, MiiluxProtection 500, Armstal 500, SweborArmor 560, as well as Hardox 500 steels.

3. Steels which are not inclined towards afterhardening under condition of welding thermal cycle action. Metal of weld zone of these steels in all cooling rates range is characterized by final hardness lower than 48 HRC. There are Quardian 500, Protac 500 and Weldox 1300 steels.

Investigated heat of Toolox 33 steel also demonstrates hardness of HAZ of weld area rather low than 48 HRC. Nevertheless, it may be seen that this material is of low-sensitive to welding heat, because in all cooling rates hardness range of weld zone is in fact invariable and is about 46 HRC. It may be supposed that the heats of this steel with increased carbon content shall provide proper level of hardness.

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АНАЛІЗ ФАЗОВИХ ПЕРЕТВОРЕНЬ В ЗВАРЮВАЛЬНІЙ ЗОНІ ТЕРМІЧНОГО ВПЛИВУ ЛЕГОВАНИХ ВИСОКОМІЦНИХ СТАЛЕЙ

В роботі проаналізовано принципи легування високоміцних загартовано-відпущених сталей, що застосовуються для протикульового захисту, а також вплив окремих легувальних елементів на процеси гартування та відпуску цих сталей внаслідок дії зварювального тепла. Обрано 15 сталей різних плавок, що застосовуються при виготовленні зварних корпусів бойових броньованих машин. Для обраних матеріалів чисельно побудовано термокінетичні діаграми розпаду переохолодженого аустеніту, визначено фазовий склад та механічні властивості металу навколошовної ділянки при швидкостях охолодження, типових для механізованого зварювання у захисному газі. За результатами проведеного розрахункового аналізу визначено матеріали, що не зазнають знеміцнення в усьому діапазоні досліджених швидкостей охолодження. [dx.doi.org/10.29010/086.7]

Ключові слова: *леговані високоміцні загартовано-відпущені сталі; знеміцнення зварювальної зони термічного впливу; CALPHAD; термокінетичні діаграми; фазовий склад та твердість сталей.*

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