Archives of Materials Science and Engineering

Volume 64
Issue 2
December 2013
Pages 228-236

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Reason analysis of welded joints cracking joints in membrane wall elements as a basis for selection of the chemical composition of new generation low-alloy bainitic steel on evaporator collectors for boilers with supercritical working parameters

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Received 12.11.2013; published in revised form 01.12.2013

ABSTRACT

Purpose: The aim of the paper was to assess the impact of the chemical composition and the cooling rate on the type of microstructure, the level of mechanical properties and crack sensitivity of welded joints of membrane walls of the evaporator collector for boilers made of new generation low-alloy bainitic steels for power engineering for the application in boilers with supercritical parameters.

Design/methodology/approach: Through SEM observation using the EBSD technique occurring types of microstructures, depending on the chemical composition and cooling speed of tubes and flat bars made of 7CrMoVTiB10 - 10 steels assigned for membrane walls of the evaporator collectors for boilers have been revealed. For each types of microstructure mechanical properties have been determined. The achieved results have been referred to the designated weldability factors; chemical carbon equivalent C_e and the fracture sensitivity parameter associated with the phase transitions of P_{cm} .

Findings: The influence of the chemical composition and the cooling rate on the formed microstructure and the corresponding level of mechanical properties and the value of carbon equivalent value C_e and the fracture sensitivity parameter due to 7CrMoVTiB10-10 steel welding.

Originality/value: Applied methodology and a proposed modification of the chemical composition will be used by manufacturers in modifying and developing new technology of manufacturing membrane walls of the evaporator collectors for boilers made of new generation low-alloy bainitic steels for power engineering.

Keywords: CrWVNb9-6 (P23) steel; 7CrMoVTiB10-10 (P24) steel; Microstructure; Mechanical properties

Reference to this paper should be given in the following way:

J. Dobrzański, Reason analysis of welded joints cracking joints in membrane wall elements as a basis for selection of the chemical composition of new generation low-alloy bainitic steel on evaporator collectors for boilers with supercritical working parameters, Archives of Materials Science and Engineering 64/2 (2013) 228-236.

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

An important element of economic development in Poland is the development of the power engineering. Lack of power engineering development can be a serious brake to that development. Still the participation of coal as a fuel will be dominant. Therefore, the construction of new coal fired power unit is another important step in its development in Poland. Reducing emissions of harmful substances into the atmosphere, to which Poland is obliged under EU directive allows for building new power units with supercritical parameters only. Those units emit reduced amount of harmful substances for produced energy unit. They are characterized by high efficiency and high working parameters of boilers (pressure ca. 28.5 MPa, temperature of ca. 600°C). It requires the application of new materials and working out new technological processes of those materials on numerous components in the pressure part of boilers and turbines and. In that way the material barrier difficult to overcome in the development of those devices has appeared.

One of the major problems that has appeared is the selection and application of new material for gas-tight water walls of an evaporator collector. Meeting high requirements of material work in a continuous manner at temperature up to 550°C and pressure of 28.5 MPa, forced to search for new low-alloy bainitic steel having high yield point at elevated temperature (R_e^t) and the high creep strength (R_m) at high enough plastic properties, for the elements of the evaporator collector for the boiler.

At first in Japan 7CrWVNb9-6 (T23) steel was formed by Sumitomo, and then in Europe 7CrMoVTiB10-10 (T24) steel - by Vallourec & Mannesmann.

The development of low-alloy chromium steel with molybdenum having bainitic structure designed to work in creep conditions is shown in Fig. 1 .

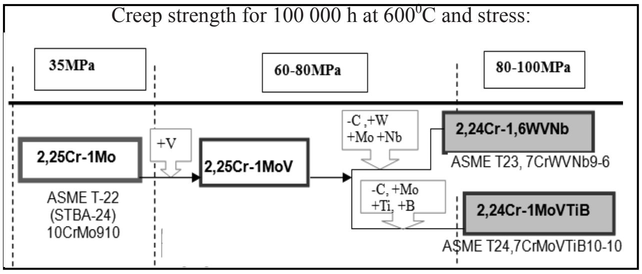

Fig. 1. Development of low-alloy bainitic chromium-molybdenum steel to work in creep conditions [1]

7CrMoVTiB10-10 steel is currently used in Europe for many new power plants for those items. However, it turned out to be difficult material to process and make segments of membrane walls and the installation of the evaporator collector for the boiler on an object without heat treatment after welding [1-29].

Below an analysis of the crack sensitivity of those steels after welding because of their microstructure and chemical composition have been made. In addition, approaches to lessen or eliminate crack sensitivity after welding have been proposed.

2. The microstructure of low-alloy bainitic steels for power engineering on the basis of the analysis of TTTc curves

Operational properties of the material depend on chemical composition and production technology of metallurgic product, and then from the process of processing and manufacturing of devices and their components. The type of the obtained microstructure and the form and the participation of given phase components determines the level and the mutual relations, especially between strength and plastic properties. The phase composition and microstructure form also depend on the cooling rate of heat treatment used in manufacturing process. The type of microstructure and its phase composition depends on the cooling rate is illustrated by TTT_c curves characteristic for each material. TTT_c curves of 7CrWVNb9-6 and 7CrMoVTiB10-10 new generation low-alloy bainitic steel compared to 10CrMo9-10 basic steel is shown in Fig. 2. Typical images of obtained microstructure of those steels observed in a scanning electron microscope for the selected range of the cooling rates which the most often appear in practice are shown in Fig. 3. 10CrMo9-10 steel structure in the initial state that is after heat treatment relying on normalizing at the temperature of 930-960˚C and tempering at the temperature of 730-760˚C is ferrite with bainite and often fine precipitations of $M_{23}C_6$ carbide occurring in the boundaries of ferrite grains. In areas of bainite, usually irregularly shaped, precipitates of M_3C and Mo_2C carbides (Fig. 3a), which are fine, evenly enough distributed, appear.

However, 7CrWVNb9-6 and 7CrMoVTiB10-10 steels are used after normalizing at temperature 1040-1080˚C and tempering at 730-780°C. 7CrWVNb9-6 steel after such heat treatment is characterized by structure of bainite with martensite or bainitic one with $M_{23}C_6$ carbide precipitates at both grain boundaries of former austenite and carbides/nitrides of MX type, mainly niobium, vanadium and tungsten inside the area of bainite. The form of occurring bainite is the most often lamellar bainite differing in lamella form and size, depending on the chemical composition and cooling conditions (Fig. 3b). Also 7CrMoVTiB10-10 steel structure is the dominant phase component is bainite, which form may be from the characteristic for upper bainite through granular bainite, lower bainite in the form of fine lamellas. Moreover, typical tempered martensite with a few grains of ferrite often appears. In the areas of tempered bainite and martensite of that steel in spite of $M_{23}C_6$ and Mo_2C carbides and fine-dispersed carbides/nitrides of MX type mainly with boron and vanadium appear (Fig. 3c) .

The form of occurring microstructure of tested steels differentiate their crack sensitivity. The greater portion of lamellar bainite and martensite, the greater the possibility of the occurrence of cracks in welded joints of manufactured devices. Mainly it applies to technological processes for manufacturing elements of devices made of 7CrWVNb9-6 and 7CrMoVTiB10-10 steels involving welding, but without heat treatment after welding.

Microstructure consisting of lamellar bainite and martensite with dispersed precipitates of carbides and carbide-nitrides, appearing in those steels gives high strength properties.

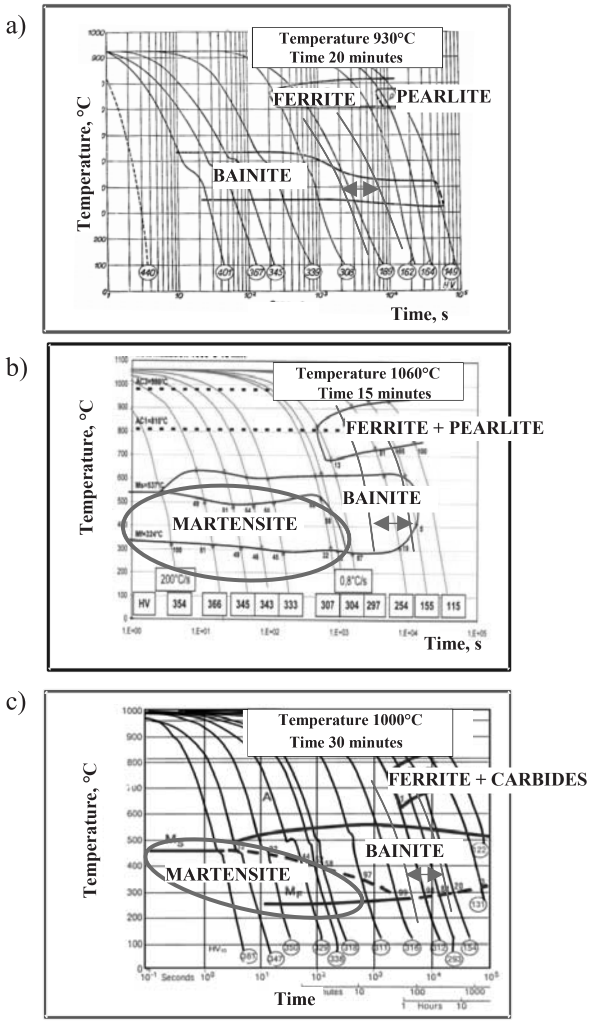

Fig. 2. Comparison of supercooled austenite continuous cooling transformation diagram of (TTT_c) of selected low-alloy bainitic steels for power engineering: a) 10CrMo9-10, b)7CrWVNb9-6, c) 7CrMoVTiB10-10

High strength properties are accompanied by a sufficiently high level of plastic properties. As a result of the welding process, due to the high cooling rate, the weld material is strengthened. It is shown by very high hardness of fine-lath martensite with a high level of internal stress. It results in excessive crack sensitivity in the joint elements of 7CrWVNb9-6 and 7CrMoVTiB10-6-10 steels. Those problems do not occur in the elements of devices manufactured from 10CrMo9-10 steel. In its microstructure lamellar bainite, and martensite do not occur in practice.

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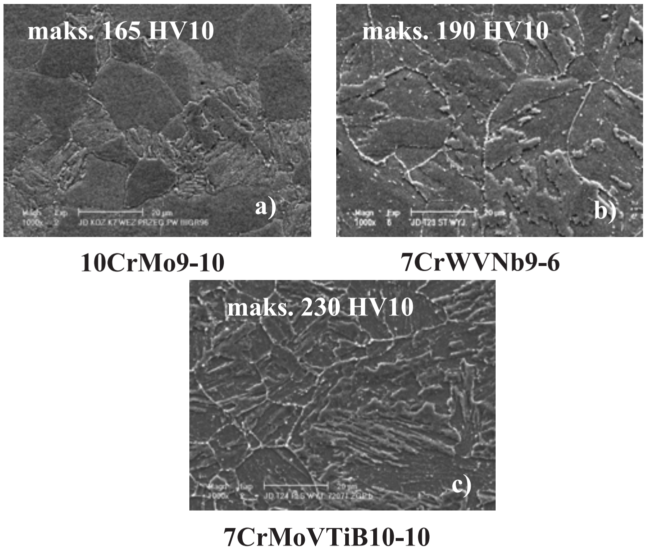


Fig. 3. Comparison of microstructures of selected low-alloy bainitic steels for power engineering, the most commonly appearing in practice: a) 10CrMo9-10, b) 7CrWVNb9-6, c) 7CrMoVTiB10-10 (microstructure observed in a scanning electron microscope)

3. Influence of chemical composition and the cooling rate of the type of appearing microstructure

The form of the microstructure of 7CrWVNb9-6 and 7CrMoVTiB10-10 steels used on the membrane walls performed without heat treatment after welding is important in the technological process of their manufacturing. In spite of the weld material of the martensitic structure the microstructure type of tubes and the flat bars used in their manufacturing process may have a significant impact on the level of internal stresses after welding thus determining crack sensitivity.

On the basis of achieved own research results of materials of tubes and flat bars it has been attempted to analyse the reasons for obtaining the microstructure with different form of bainite and martensite occurrence and its effect on the level of mechanical properties in relation to the minimum material requirements according to the standard specification.

The analysis has been made on the basis of the research results of 7CrMoVTiB10-10 steel, which has much higher crack sensitivity of produced homogeneous welded joints.

The analysis was performed on tubes chosen from four melt with the chemical composition presented in Table 1 against the requirements of PN-EN 10216-2 standard. Similar studies have been done for materials of flat bars made of that steel [30].

Table 1.
Chemical composition of material of analysed tubes made of 7CrMoVTiB10-10 steel with differentiated form of bainite in the microstructure

No[2)]	size.	Chemical composition [%] [1)]						
	mm	C	Mn	Cr	Mo	Ti	N	B
1	42.4x7.1	0.037	0.45	2.51	0.99	0.054	0.0051	0.0019
2	33.7x5.0	0.098	0.53	2.57	0.96	0.079	0.0066	0.0043
3	42.2x7.1	0.088	0.55	2.65	0.97	0.057	0.0080	0.0042
4	33.7x5.0	0.059	0.56	2.64	0.94	0.057	0.0070	0.0014
Requirements according to PN-EN 10216-2		0.05 0.10	0.15 0.35	2.20 2.60	0.90 1.10	0.05 0.10	<0.010	0.015 0.070

[1)] Si; 0.22-0.28 (0.15-0.45). V; 0.23 (0.20-0.30)
[2)] 1-structure of granular bainite; 2-structure of mixture of bainite and granular bainite; 3-structure of bainite with ferrite; 4-structure of lower bainite with martensite

The estimated cooling rate for tubes made of the steel is shown in a graphical form against continuous cooling transformation diagram of austenite (TTT_c) in Fig. 4.

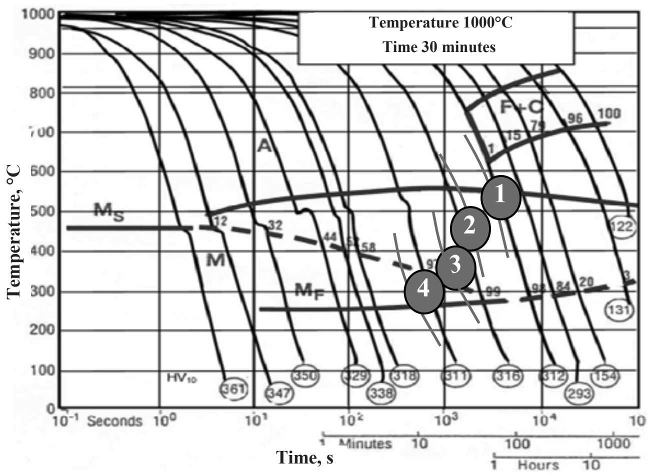


Fig. 4. The estimated cooling rate after austenitising tubes made of 7CrMoVTiB10-10 steel against the background of continuous cooling transformation diagram (TTT_c) with geometric dimensions: ϕ 42,4x7,1 mm, 2) ϕ 33.7x5.0 mm, 3) ϕ 42.4x7.1 mm, 4) ϕ 33.7x5.0 mm

The obtained microstructure of the tube material, observed in a scanning electron microscope, from granular bainite to lower lath bainite with martensite is shown in Fig. 5. To each disclosed microstructures the achieved level of hardness measured by Vickers method has been assigned (HV10).

For the disclosed form of the microstructure using the EBSD technique in the scanning electron microscope, some characteristic parameters have been pointed out. Examples of the obtained results of selected types of microstructures which give the possibility to point out an equivalent grain shape, grain shape factor and the estimation of given phases in the material have been shown in Figs. 6-9.

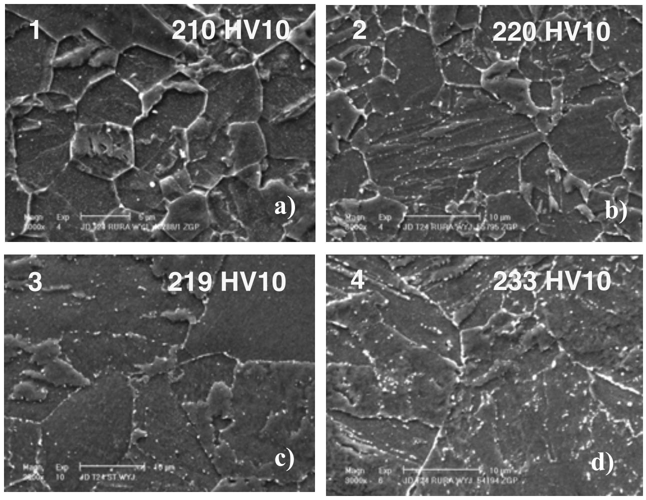


Fig. 5. The microstructure of tubes made of 7CrMoVTiB10-10 steel, depending on the chemical composition and the cooling rate: a) denotation 1; Structure of granular bainite. Around the areas of granular bainite, ferrite grains with huge amount of very fine precipitates - granular bainite portion: 66%, bainite portion: 34%; b) denotation 2; Mixed structure of granular bainite and bainite. Areas around lath bainite, bainite grains with huge amount of very fine precipitates - granular bainite portion: 63%, bainite portion: 37%; c) denotation 3; Structure of bainite with ferrite. At grain boundaries fine precipitates forming chains - bainite portion: 100%; d) denotation 4; Structure of lower bainite with martensite

At grain boundaries fine precipitates forming chains. Inside the diversified sizes of bainite and martensite areas on the lath borders, numerous very fine precipitates - bainite portion: 65%, martensite portion: 35%.

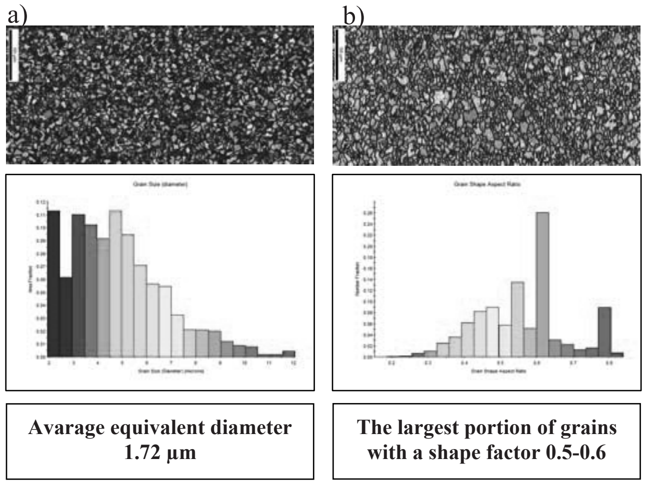
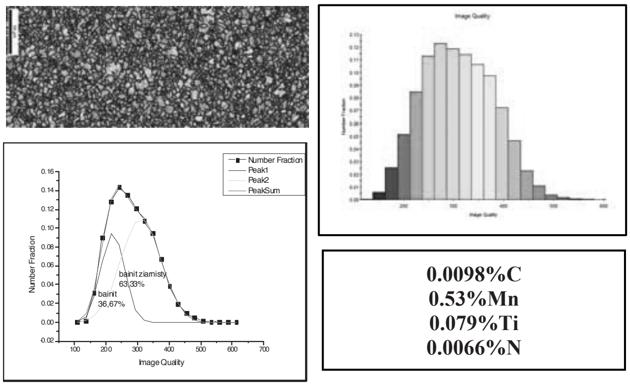


Fig. 6. Characteristic parameters of microstructure of the granular bainite and bainite of tube material made of 7CrMoVTiB10-10 steel for making the membrane walls of the evaporator collector for the boiler with supercritical working parameters disclosed in SEM by EBSD technique: a) the distribution of an average equivalent grain diameter; b) the distribution of grain shape



granular bainite 63%, bainite 37%

Fig. 7. Portion of granular bainite and bainite in the microstructure of tube material made of 7CrMoVTiB10-10 steel assigned for the manufacturing membrane walls of the evaporator collector for the boiler with supercritical working parameters disclosed in SEM by the use of EBSD technique (such material as in Fig. 5)

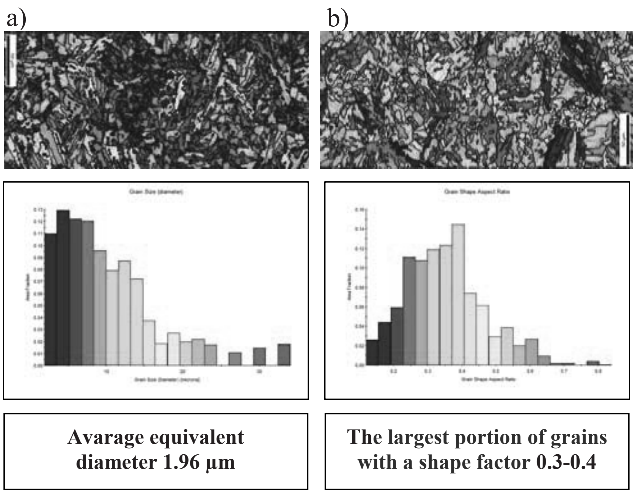
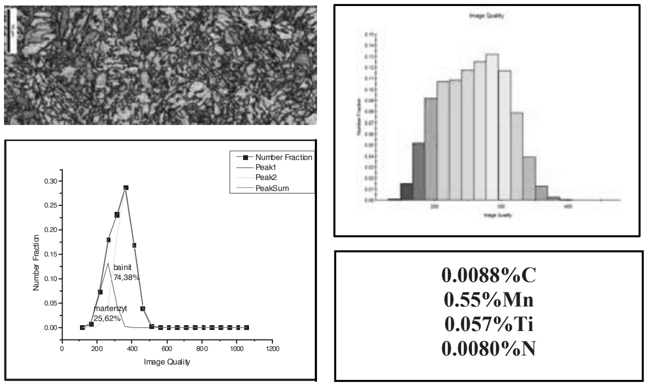


Fig. 8. Characteristic parameters of the microstructure of lower bainite with martensite of tube material made of 7CrMoVTiB10-10 steel for making the membrane walls of the evaporator collector for the boiler with supercritical working parameters disclosed in SEM by the use of EBSD technique: a) the distribution of an average equivalent grain diameter; b) the distribution of grain shape

4. Mechanical properties depending on the type of the obtained microstructure

The form of obtained microstructure has an influence on the level of obtained mechanical properties of tubes and flat bars. For each of the tested materials mechanical properties have been determined. The obtained results have been shown in the form of the dependence of material properties from a form of occurring microstructure. The denotation has been assigned to each analyzed material with a different form of the occurring microstructure. Tube materials have been denoted :- structure of granular bainite denotation 1 - structure of granular bainite with bainite denotation 2 - structure of bainite with ferrite, denotation 3 - structure of lower bainite with martensite denotation 4 .



lath bainite75%, martensite 25%

Fig. 9. The portion of lower bainite with martensite in the microstructure of tube material made of 7CrMoVTiB10-10 steel for the membrane walls of the evaporator collector for the boiler with supercritical working parameters disclosed in SEM by the use of EBSD technique (such material as in Fig. 8)

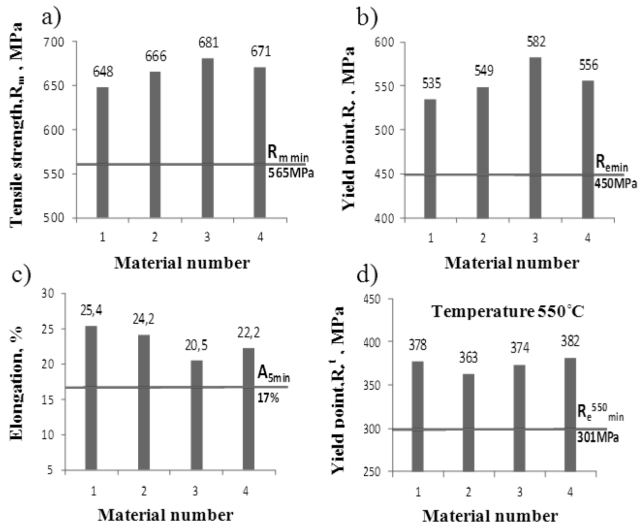


Fig. 10. Mechanical properties of tubes made of 7CrMoVTiB10-10 steel for gas-tight water wall elements made of materials in various forms of bainite and martensite portion: a) tensile strength R_m at the room temperature, b) yield strength of R_e at the room temperature, c) elongation A5 in a tensile test at the room temperature, d) yield strength R_e^t at temperature 550°C; Denotation 1 - Structure of granular bainite with bainite (66%/34%), Denotation 2 - Mixed structure of granular bainite with bainite (63%/37%), Denotation 3 - Structure of bainite with ferrite (100%/bainite) Denotation 4 - Structure of lower bainite with martensite (65%/35%)

The dependence of tensile strength R_m at the room temperature in a form of bainite and martensite portion, is shown in the graphical form of tube material in Fig. 10a. A similar dependence of yield strength R_e is shown in Fig. 10b, and yield strength R_e^t at the temperature of at 550°C in Fig. 10d. However, in Fig. 10c, changes of elongation A_5 of material in a tensile test at the room temperature, depending on the form of bainite and martensite portion have been shown in a graphical form.

The dependence of impact energy of tubes made of 7CrMoVTiB10-10 steel for gas-tight water wall elements from the form of bainite and martensite portion at the room temperature have been shown in Fig. 11. Similar dependences of materials microstructure form of materials of tubes and flat bars from impact energy measured at different temperature level of the research for pointing out brittle fracture appearance transition temperature has been shown in Fig. 12. The obtained values have been related to the minimum requirements included in the standard specification for metallurgic products made of the steel.

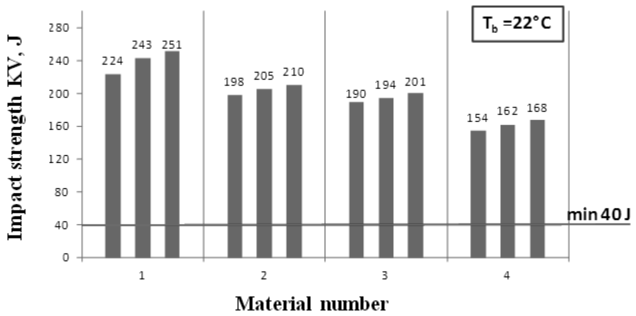


Fig. 11. Impact energy of tubes made of 7CrMoVTiB10-10 steel at the room temperature for gas-tight water wall elements of materials with various forms of bainite and martensite portion Denotation 1; Structure of granular bainite with bainite (66%/34%), Denotation 2, Mixed structure of granular bainite with bainite (63%/37%), Denotation 3; Structure of bainite with ferrite (100%/bainite), Denotation 4, Structure of lower bainite with martensite (65%/35%)

Summing up it can be claimed that the set of strength and plastic properties regardless of the type of occurring microstructure and a form of occurring main phase components in the material of the tubes and flat bars made of 7CrMoVTiB10-10 steel is at the required level. However, occurring microstructure being a mixture of bainite in a lamellar form with martensite are characterized by a state of considerable internal stresses. This condition has a significant impact on the welding process and its results if heat treatment is not made after it. A type of such structure should be considered as undesirable one.

Analysing the research results of the obtained mechanical properties for the different states of the microstructure of tubes and flat bars materials made of 7CrMoVTiB10-10 steel it can be stated that with the appearance of the structure of lower bainite in the form of lath and martensite there is an increase in tensile strength of ca. 650 to ca.680 MPa for tube material and ca. 630 to ca. 700 MPa for flat bars material with a simultaneous increase in yield strength of ca. 510 to ca. 580 MPa. Also yield stress level increases from ca. 360 to ca. 380 MPa for the tubes material and from ca. 330 MPa to ca.360 flat bars material at the temperature of 550°C. All obtained results of strength properties are significantly higher than the required minimum values, both for tubes and flat bars. The increase in tensile strength results in a reduction in a tensile test of ca. 22 to ca. 20%, but those values are much higher than the required minimum of 17%.

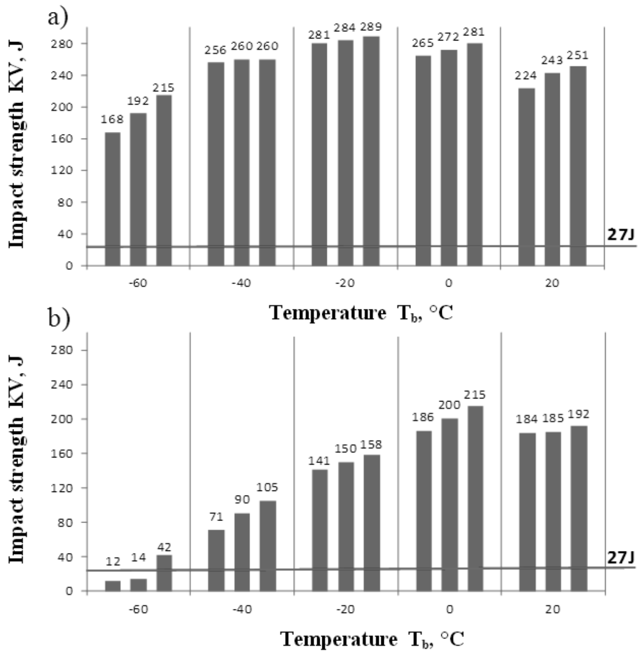


Fig. 12. Impact energy depending on the temperature of tubes material made of 7CrMoVTiB10-10 steel at the room temperature with various forms of bainite and martensite portion: a) Denotation 1; Structure of granular bainite with bainite (66%/34 %), b) Denotation 4, Structure of lower bainite with martensite (65%/35%)

Also differences in the level of impact energy, which decreases from ca. 240 J for tubes material and ca. 200 J for the flat bars on the structure with essential portion of granular bainite to the value of ca. 150 to ca. 170 J for tubes and flat bars material of the structure of lower bainite with martensite. The achieved values are much higher than the minimum required value 40 J. Depending on the occurring microstructure different level of brittle fracture appearance temperature has been obtained.

For tubes material with a substantial portion in the structure of granular bainite, the temperature is below -60°C. For tubes material with the structure of lower bainite with martensite it equals ca. -50°C or tube material with the structure of granular bainite with martensite it is below -60°C. Similar trends can be observed for the flat bars material, even though for their structure being the mixture of lower bainite with martensite brittle fracture appearance temperature is below -60°C.

5. Conclusions

7CrWVNb9-6 and 7CrMoVTiB10-10 steels are modern materials from the group of the new generation steel of modern bainite characterized by high strength properties, including creep strength, simultaneously with kept high plastic properties. It has seemed that their application in power engineering for membrane walls would meet the expectations of designers and technologists in the range of the required load for the evaporator collector for boilers with supercritical working parameters (p_r=28.5 MPa; T_r=550°C). In practice it has turned out that their tendency, particularly of 7CrMoVTiB10-10 steel, to form lamellar structures being a mixture of the lower bainite with martensite is an obstacle in the outworking and application of welding technology in industrial practice, making peripheral and fillet joints, which enables the production of gas-tight water wall segments without heat treatment after welding.

In Table 2 mechanical properties, that is, tensile strength, yield strength at the room temperature, yield stress at the elevated temperature, impact energy at the room temperature and brittle fracture appearance temperature and hardness, obtained for tubes and flat bars materials of various structures from being a mixture of granular bainite and bainite to lower bainite with mixture of martensite have been gathered. Microstructure with the portion of lower bainite with martensite are characterized by slightly higher strength properties, but with slightly reduced plastic properties, but all fulfil minimum requirements for the tubes and flat bars made of 7CrMoVTiB10-10 steel. Therefore narrowing the chemical composition of the steel in the range of some elements what could significantly reduce the tendency to form lamellar structures in the manufactured tubes and flat bars should be considered. In a similar way the selection of the chemical composition of the welding material (wire , flux) should be made. The applied modified welding technology should also significantly reduce or eliminate the possibility of appearing of such structure in the weld.

The result of the analysis of crack sensitivity of selected low-alloy steel of Cr-Mo and Cr-Mo type with microaddition based on the calculated carbon chemical equivalent C_e and fracture sensitivity parameter P_{cm} associated with the phase transitions of the required standard specification for the minimum and maximum chemical composition are summarized in Table 3.

C_e ratio and parameter P_{cm} have been pointed out from the set of equations given below the table [31,32]. It is assumed that material is well- weldable, where $C_e \leq 0.45$ and then there is no cold crack sensitivity in it. When the value of $C_e > 0.45$ then with its increase, the sensitivity increases, although it is not the only element that decides about it. The impact has also the level of obtained hardness in HAZ and the weld and fracture sensitivity parameter P_{cm} associated with the phase transitions. The influence of P_{cm} parameter, however, is closely associated with the level of preheating temperature before welding. Those elements should therefore be analyzed together.

In Table 4 the obtained values of equivalent C_e and parameter P_{cm} for the analysed materials of tubes and flat bars made of 7CrMoVTiB10-10 steels with different structures, being a mixture of granular bainite and bainite to lower bainite with martensite have been gathered. When the chemical equivalent C_e for the tested steel is ca. 0.9, and more, and at the same time fracture sensitivity parameter P_{cm} associated with the phase transitions is above ca. 0.34, it can be expected that lower bainite with martensite can appear. However, when the temperature level of preheating before welding is too low then this sensivity may be revealed for the material with chemical composition, which corresponds to the lower value of the parameter P_{cm}.

Table 2.
Juxtaposition of test results of microstructure parameters and mechanical properties of the tube and flat bars material made of 7CrMoVTiB10-10 steel with diversified form of bainite and martensite portion in the microstructure

Den.	Mettallurgic product Dimensions mm	Microstructure parameters: Granular bainite/ martensite portion, %	Microstructure parameters: Average equivalent diameter of grains, μm / Grain shape shape ratio	Mechanical properties: Tensile strength R_m, MPa / Hardness HV10	Yield point R_e, MPa / Yield point at 550°C R_e^{550}, MPa	Impact energy KV, J / Brittle fracture appearance temperature T_{50}, °C
TUBES						
1	tube Ø42.4x7.1	65/35/0	1.91	648	535	239
			0.5-0.6	210	378	- 60
2	tube Ø33.7x5.0	63/37/0	1.84	666	549	204
			0.5-0.6	220	363	- 60
3	tube Ø42.4x7.1	0/75/25	1.73	681	582	195
			0.3-0.4	219	374	- 50
4	tube Ø33.7x5.0	0/65/35	2.75	671	556	187
			< 0.5	233	382	- 50
FLAT BARS						
1	Flat bar 79.1x8.0	52/48/0	1.72	628	501	209
			0.5-0.6	215	329	- 60
2	Flat bar 27.8x8.0	65/35/0	2.18	621	518	267
			0.3-0.6	210	359	- 60
3	Flat bar 77.0x6.0	0/69/31	1.96	714	558	178
			< 0.5	232	349	- 60

Table 3.
Weldability factors of selected low-alloy steels for power engineering depending on their chemical composition in accordance with the applicable standard specification

Steel grade	Chemical carbon equivalent C_e		Fracture sensitivity parameter associated with the phase transitions P_{cm}	
	Min.	Max.	Min.	Max.
13CrMo4-5	0.347	0.647	0.197	0.332
10CrMo9-10	0.727	1.007	0.265	0.410
7CrWVNb9-6	0.760	1.017	0.335	0.733
7CrMoVTiB10-10	0.530	0.840	0.180	0.327
Cold crack sensitivity	over 0.45		Depending on preheating temperature	

$$C_e = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \ \% \qquad [31]$$

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn + Cr + Cu}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \ \% \qquad [32]$$

Table 4.
Weldability factors of tested tubes and flat bars of 7CrMoVTiB10 low-alloy steel for elements of gas-tight water wall of the evaporator collector for boilers with supercritical working parameters for selected types of obtained types of microstructure dependent on the chemical composition of the steel and the cooling rate

Den.	Microstructure		Chemical carbon equivalent C_e	Fracture sensitivity parameter associated with the phase transitions P_{cm}
	Structure type	Portion of basic phase components in structure; granular bainite/ bainite / martensite, %		
TUBES				
1	Granular banite with bainite	65/35/0	0.8580	0.2928
2	Granular banite with bainite	63/37/0	0.9338	0.3688
3	Bainite with martensite	0/75/25	0.9497	0.3650
4	Bainite with martenzite	0/65/35	0.9144	0.3200
FLAT BARS				
1	Granular banite with bainite	52/48/0	0.9317	0.3421
2	Granular banite with bainite	65/35/0	0.8884	0.3171
3	bainite with martensite	0/69/31	0.9084	0.3445

It is necessary to consider the proposal of a new type of steel with the chemical composition so chosen to minimize a tendency to the formation of lamellar structures of lower bainite with martensite. The selection of the chemical composition would also include welding materials. It is expected that such material is likely to be characterized though slightly lower basic strength properties and creep strength compared to those of 7CrMoVTiB10-10 steel, however by higher than those of conventional Cr-Mo low-alloy binary steels, previously used [33]. The reason analysis of cracking of welded joints of gas-tight water walls of the steel, on the basis of tests of welded joints made by applicable technology also allowed to propose new solutions using the steel, which has been discussed in [34].

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