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

J. Dobrzański*
Institute for Ferrous Metallurgy, ul. K. Miarki 12, 44-100 Gliwice, Poland
* Corresponding e-mail address: jdobrzanski@imz.pl

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ABSTRACT

Purpose: The aim of the study was to evaluate crack sensibility of low-alloy bainitic steel 7CrWVNb9-6 (P23) and 7CrMoVTiB10-10 (P24) after welding on the basis of the results of welded gas-tight tubular wall elements and to propose changes in the manufacturing technology of the evaporator collector with supercritical working parameters of that steel group.

Design/methodology/approach: On the basis of out carried macroscopic, microscopic researches in SEM using EBSD technique and material hardness measurements of circumferential and fillet welded joints the places of occurrence and the character of occurring cracks have been determined.

Findings: The influence of flat bars forms, welding parameters, the nature of joint penetration on crack sensibility in circumferential and fillet welded joints of membrane walls of the evaporator collector made of new generation low-alloy bainitic steels for power engineering intended for use in boilers with supercritical working parameters.

Practical implications: Obtained results and out carried reason analysis of cracking of welded joints of membrane walls made of new generation low-alloy bainitic steels for power engineering allowed to propose three ways of conduct as far as changes and selection of manufacturing technologies of evaporator collector reducing or eliminating crack sensibility of welded joints.

Originality/value: The applied methodology, adopted procedure and proposed changes in the manufacturing of membrane walls, installation and repair of the evaporator collector with supercritical parameters made of new generation low-alloy bainitic steels for power engineering will be used by manufacturers in modifying and developing new applied technologies of manufacturing those elements.

Keywords: Steel 7CrWVNb9-6 (P23); Steel 7CrMoVTiB10-10 (P24); Welding

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MATERIALS

1. Introduction

Boilers with supercritical working parameters, having the required low emission of harmful substances into the atmosphere require higher and higher performance of exhaust steam. The increase of those parameters requires the exploration and the application of new materials with higher and higher tensile and more complex technological process of making those components of the boiler pressure parts. Among the critical elements of boiler pressure parts there should be distinguished membrane walls, which materials in systems with supercritical parameters can operate at up to 550 º C. For those elements new generation low-alloy steels of 2.25%Cr-1%Mo type with micro-additions, in Japan 7CrWVNb9-6 (P23) steel and in Europe 7CrMoVTiB10-10 (P24) steel have been developed and applied. As a result of widely realized researches, within the European structures of COST 511, 522 and 536 welding materials and technologies of manufacturing out of them boiler components have been worked out.

For those steels the required set of working features, especially creep strength while maintaining sufficiently high plastic properties and the ability to weld was obtained by appropriate modification of the chemical composition of steels containing ca. 2.25% Cr with molybdenum, traditionally used and tested in operational conditions. In the proposed new steels the increase of strength properties obtained by incorporating an appropriate amount of V, for 7CrWVNb9-6 the addition of W and microaddition of Nb and N, and for 7CrMoVTiB10-10, at a sufficiently high content of Mo in spite of V the addition of B, Ti and N have been introduced [2-9]. The juxtaposition of the required chemical composition for the application of bainitic steels at elevated temperature for the membrane wall elements of a evaporator collector are summarized in Table 1.

Table 1.
Juxtaposition of chemical composition of new bainitic steels applied for membrane walls in boilers with supercritical parameters

Steel type	Element contents, %				
	C	Cr	Mo	V	others
7CrWVNb9-6 (T/P23) 1)	0.04 0.10	1.90 2.60	to 0.30	0.20 0.30	W 1.45-1.75
					Nb 0.02-0.08
					N to 0.010
7CrMoVTiB10-10 (T/P24) 2) W-1.7378	0.05 0.095	2.20 2.60	0.90 1.10	0.20 0.30	N to 0.010
					B 0.0015-0.0070
					Ti 0.05-0.10

1) Si to 0.50; Mn 0.30-0.60; 2) Si 0.15-0.45; Mn 0.30-0.70

7CrMoVTiB10-10 steel is currently used in Europe in many new power plants on those items. However, it turned out to be difficult material to process and make the segments of membrane walls and installation of the evaporator collector in an object without heat treatment after welding [1-30]. Below on the basis of the analysis of obtained results of manufactured gas-tight tubular wall segments by the use of required technology the tendency of those steels to crack after welding have been evaluated. On the basis of that analysis including the selected essential stages of applied technology, solutions have been proposed to lessen or eliminate the tendency to crack after welding including the application requirements have been proposed. Selected stages for the analysis are: requirements for fillet joints, pre-heating, flat bar form before welding, welding parameters, the level of fillet joint penetration, making circumferential joints.

2. Requirements for one-stitch welded joints of membrane wall

Requirements of one-stitch welded joints of gas-tight water walls, regardless of a method of welding or submerged arc or TIG method include maximum allowable size of an unmelted gap between a tube and a flat bar and minimum thickness of an unmelted tube.

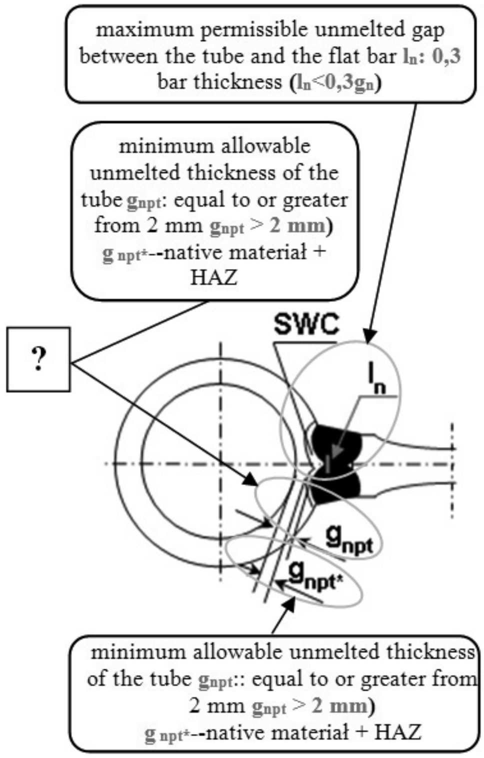

Fig. 1. Requirements for fillet welded joints of gas-tight water walls of low-alloy bainitic steels: S_n - nominal width, S_d - exact width

The required critical size for such welded joints made of 7CrMoVTiB10 -10 steel has been take to the consideration as for the tight walls made of far the most commonly used low-alloy binary steel of 16Mo3 and 13CrMo4-5 type. Those requirements are graphically shown in Figure 1. In the case of low-alloy steel of a new generation with more complex chemical composition which is 7CrMoVTiB10-10 steel, those requirements seem to be insufficient. Tendency to form by that steel lamellar structures being a mixture of lower bainite with martensite, and after welding the appearance of "hard" martensite structure in welds, create conditions for the formation of cracks, both cold and hot ones. Then discontinuity occurring in the gap between the unmelted tube and the flat bar, are a place of the initiation of cracks. Therefore, it is necessary to accept such gaps and require full penetration (l_n=0). Also, the requirements for minimum unmelted thickness are too liberal. The minimum thickness of tube material of the structure corresponding to the structure of the tube that is without HAZ structure should not differ from the computational thickness g_o taken into consideration. Only then tube material is capable of transferring the required loads resulting from the temperature- stress parameters which have been taken into consideration. In the case of common types of microstructure in the heat affected zone, particularly when it includes entire thickness of the tube, there is no such guarantee. The actual creep strength, as well as the yield strength at the computational working temperature can be lower than the minimum required value ($R_{z\ rz}$<0,8 R_z; $R_{e\ rz}^t < R_{e\ min}^t$) for material with such microstructure. When additionally the difference between real thickness and computational thickness is small, then the material cannot bring the required loads and the loss of its continuity can appear .

3. Pre-heating

The first step in technology of making membrane walls affecting for the elimination of the tendency to crack of fillet welded joints is to preheat flat bars and tubes immediately before welding. It aims to:

a) drain any moisture contained on metallurgical products, the presence of which can cause hydrogen embrittlement,
b) minimize the amount of energy introduced during welding at the maximum possible welding speed necessary to achieve full penetration of a welded joint of a flat bar - a tube obtaining a narrow heat affected zone and HAZ structure and a weld of a suitably low hardness .

Protection against susceptibility to the occurrence of hydrogen embrittlement is to provide a preheating temperature at minimum 100˚C.

Obtaining hardness in a weld no more than of 370 HV10, and preferably less than 350 HV10, connected with the form of martensite characterized by the form of martensite plates are possible by the use of the preheating temperature of min. 150˚C, preferably between 150 and 200˚C. Appropriately selected moderate welding speed with a minimum of welding heat input gives an additional opportunity to receive such structure with a relatively narrow heat affected zone, which provides sufficient thickness of the tube bigger than computational thickness without HAZ participation.

4. Flat bar form before welding of membrane walls

In an industrial practice, because of a cost factor a flat bar of unacceptable dimensional tolerances concerning its width (S_n>>S_d) is most commonly used. It requires cold calibration, which effect is to obtain precise dimension S_d corresponding to the nominal dimension S_n(S_n=S_d). The calibration process is, however, unfavourable. It causes the thickening of a flat bar in the area of welding and the formation of micro-cracks, discontinuities and creases in the deformed area. Thickening a flat bar introduces the need to increase the amount of energy to achieve complete joint penetration between the tube and the flat bar with increased propensity for an enlarged heat affected zone, which may include the actual total thickness of the tube g_{npt} and then the state structure of the material in those areas does not guarantee the required transfer of both the foreseen computational and actual operating ones.

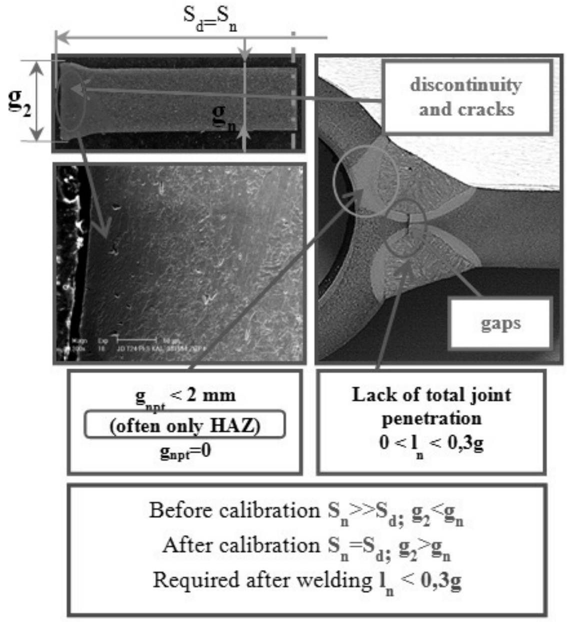

Fig. 2. The influence of the shape of the flat bar side surface in the form of steel product after the calibration prior to welding (S_n≠S_d) in the form of weld microstructure, the participation of the heat affected zone and the size of the gap of an unmelted crack of fillet welded joints of gas-tight water walls made of 7CrMoVTiB10-10 steel. S_n - nominal width , S_d - exact width , g_n - nominal thickness ; g_2 - width of a contact plane with a tube

The structure of the weld because of the possibility of the appearance of high-speed cooling after welding can be the structure of "hard" martensite with hardness greater than 450 HV10. Furthermore, in many areas, the lack of total melting of joint penetration and the appearance of the gap l_n between the flat bar and the tube (l_n>>0), which in combination with a 'hard' martensite in the weld which is a potential spot of a crack initiation and propagation, both hot and cold ones, which occur in practice.

Therefore, also for those reasons, a condition required by technology l_n≤0.3 g_n is too liberal and insufficient and does not work in industrial practice in the production of gas-tight water walls out of that steel type. The influence of the shape of the side surface of a flat bar on the form of the microstructure of the weld, the participation of heat affected zone and the size of the gap of unmelted fillet welded joints of gas-tight water walls made of 7CrMoVTiB10-10 steel on examples in an industrial practice is shown in Figures 2 and 3.

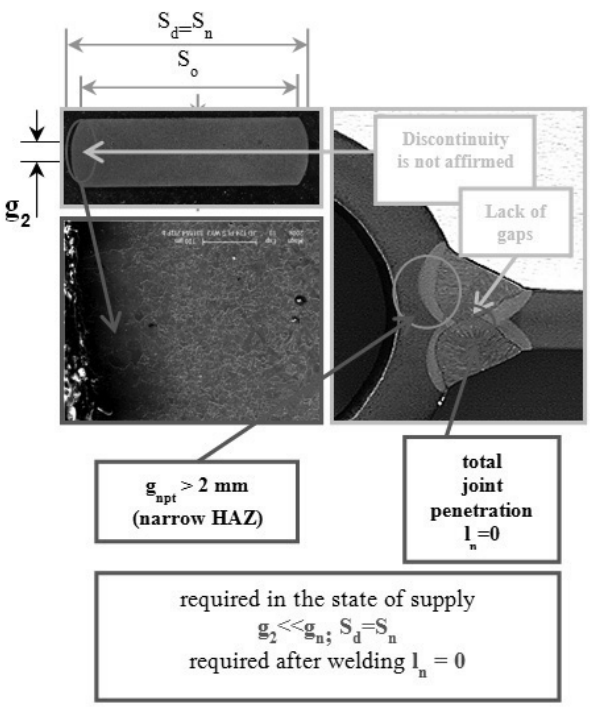

Fig. 3. The influence of the shape of the side surface in the form of a metallurgic product made in the exact required size (S_n=S_d) on the form the weld microstructure, the participation of the heat affected zone and the size of the unmelted gap of fillet welded joints of gas-tight water walls made of 7CrMoVTiB10-10 steel
S_n-nominal width, S_d-exact width, S_d-exact width, S_o-segment parallel to a flat bar width, g_n - nominal thickness; g_2-width of a contact plane with a tube

A flat bar should not have sharp edges and the suitable rounding of side surfaces being a spot of welding with the tube ($g_2 << g_n$ where: g_n - total flat bar thickness, g_2 – flat bar thickness corresponding to the plane adhesive to a tube). Then selvedge zone is free of micro-cracks and discontinuity. Due to the need to maintain the required scale according to the project it is necessary to protect the metallurgical product meeting the requirements for the shape of the side surfaces and the level of tolerance of flat bar width. Then, the shape of the adhesion surface of tube/flat bar allows to minimize energy required to obtain a welded joint tube/ a flat bar, in which weld structure will be characterised by martensite having hardness of no more than 350 HV10 and a narrow heat affected zone that ensures the minimum required unmelted tube thickness g_{npt} of at least 2 mm ($g_{npt} \geq 2$ mm). The term unmelted tube thickness g_{npt} can be understood as a part of the total actual thickness of a tube g_{rz} without the participation of a heat affected zone. At the same time, it allows to achieve the total joint penetration between a flat bar and a tube eliminating potential initiation and growth of micro-cracks Then the maximum permitted unmelted gap l_n is zero (l_n = 0) because the total actual thickness g_{rz} is most often much higher than the required computational one ($g_{rz} > g_o$) the fulfillment of the condition $g_{npt} \geq 2$ mm ensures the transfer of the required computational load (p_o, T_o) through the tube of membrane walls of a evaporator collector.

5. Effect of welding parameters on the weld and HAZ fillet welded joints of membrane walls

The width of the appearing heat affected zone and its structure as well as the structure of material elements of the fillet weld of elements of membrane walls made of 7CrMoVTiB10-10 steel is influenced by a number of elements of their technological process for their manufacturing. The first element of the technological process having an impact on it is preheating temperature. Its level is affected by the heating time depending on geometrical dimensions of the tube and the flat bar. Sufficiently high temperature of the tube and the flat bar immediately prior to welding enables to carry out the process of welding using less linear energy, which may have a significant impact on the rate of cooling after welding, and therefore on the type of the appearing structure in a weld and the HAZ structure and width. The higher cooling speed, the greater inclination of appearing welds of fillet welded joints to form martensite with high hardness being structure with significant internal stress level, for which, in practice, it is necessary to heat treatment after welding in order to prevent occurrence of cracks. The welding speed and the amount of necessary liner energy can also affect the shape and form of a front surface of the flat bar as shown in Figure 2. Also appearing discontinuities and creases in the selvedge zone of the flat bar after calibration in strip structure of lower bainite with martensite of the flat bar material creates favourable conditions for the occurrence of cracks after welding unless they are melted (Fig. 3). Figure 4 shows an example of fillet joints of an expected narrow heat affected zone with the structure of lower bainite which is the mixture of martensite with hardness of 350 HV10 with the structure of weld material being martensite having hardness of 390 HV10, and the tube having the structure consisting of bainite and granular bainite having hardness of 230 HV10, obtained in the industrial conditions. A distribution of hardness of the analyzed fillet welded joint is shown in Figure 4d.

Another example is a connection made with moderate length and a narrow heat affected zone. HAZ structure on both sides of the welded joint made of bainite with numerous small precipitates having hardness slightly above 200 HV10 is similar. However, the structure of the welds is varied. The structure of the weld with the moderate heat affected zone is dislocation martensite with hardness above 375 HV10. In contrast, the structure of the weld with the narrow heat affected zone is lower bainite with martensite with hardness of 350 HV10. The material of the welded tube is characterized by bainitic structure with hardness of 225 HV10 .

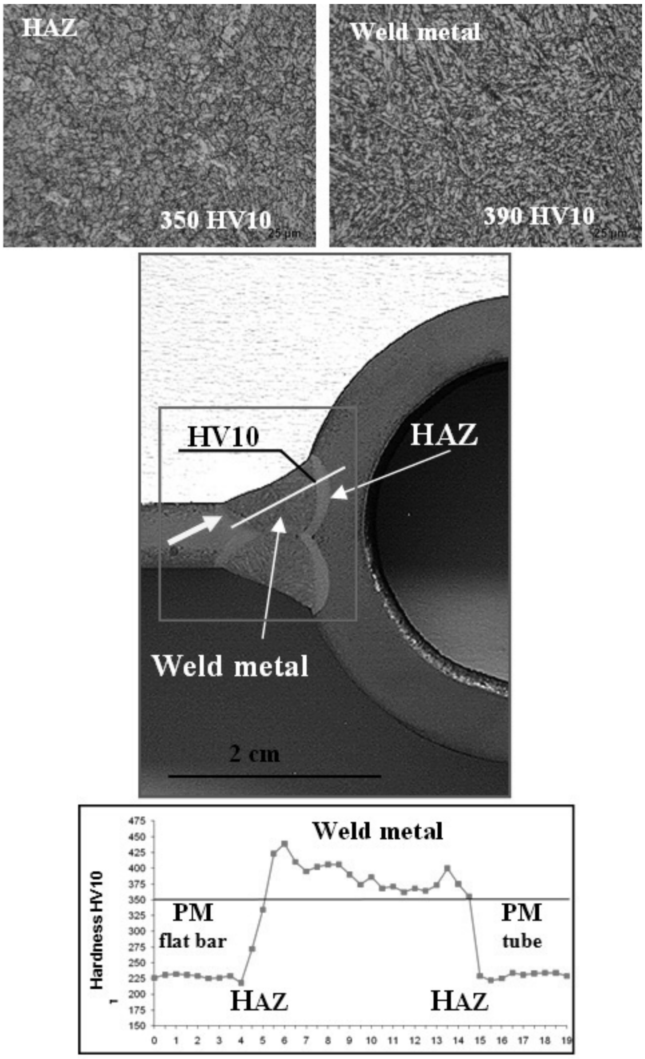

Fig. 4. The microstructure of the heat affected zone and the weld and hardness distribution in the cross section of the fillet welded joint of gas-tight water walls made of 7CrMoVTiB10-10 steel with a narrow HAZ (LM)

The differences appearing in the width of the heat affected zone and in the form of a weld structure of the material may result from the difference of a temperature level of preheating prior to welding, and the cooling rate after welding.

An example of fillet joints with a heat affected zone covering the entire thickness of a tube and moderate width of the heat affected zone is shown in Figure 5. HAZ structure on both sides of the made welded joint is similar. It is bainite with numerous fine precipitates respectively with hardness of 205 and 215 HV10 . The structure of both welds is a mixture of lower bainite with martensite with hardness respectively of 340 and 328 HV10. In contrast, the structure of the tube material is bainite with hardness of 225 HV10.

The research results in the scanning electron microscope aiming to point out basic structural components and some parameters of the occurring microstructure with the use of EBSD technique for the elements of examined welded joints confirmed the character of the occurring microstructure with the participation of the major phase components. An example of results of such researches is shown in Fig. 6 .
Depending on the level of preheating temperature prior to welding and the cooling rate after welding occurring in the heat affected zone the microstructure from granular bainite to granular bainite with fine precipitates to the lamellar microstructure of lower bainite with martensite having hardness from ca. 200 to ca. 340 HV10 can be expected. Examples of the most commonly appearing microstructures of the heat affected zone in industrial practice is shown in Figure 7.

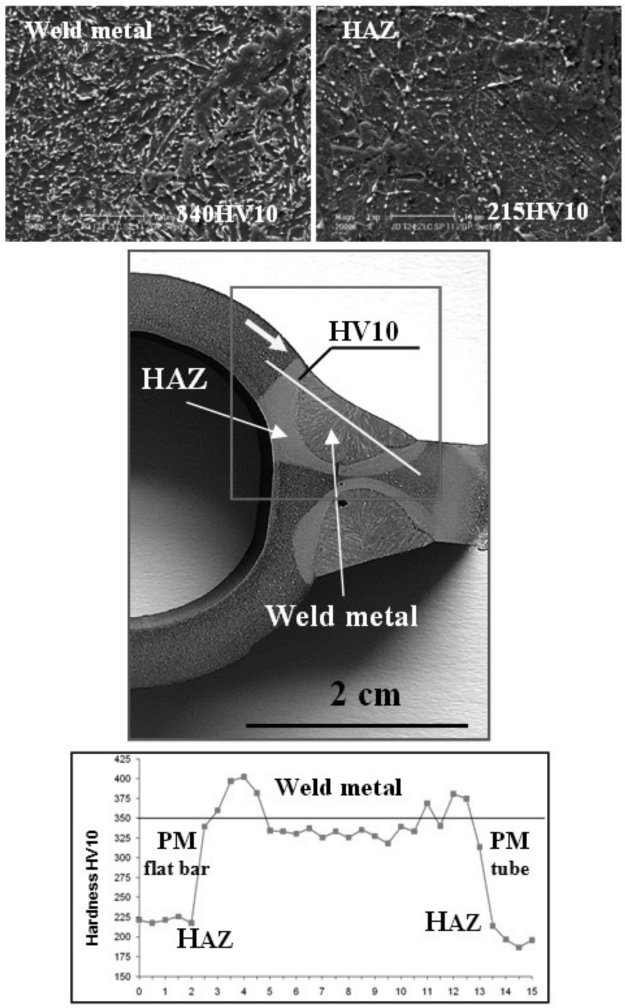

Fig. 5. The microstructure of the heat affected zone and the weld and hardness distribution in the cross section of the fillet welded joints of gas-tight water walls made of 7CrMoVTiB10-10 steel with HAZ including entire thickness of the tube (S

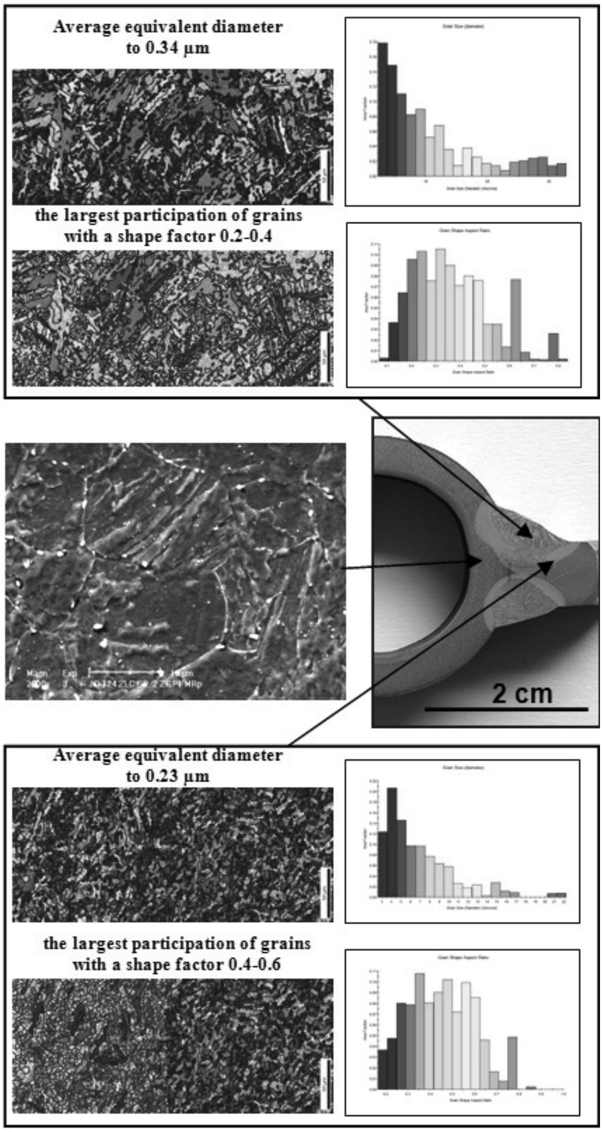

Fig. 6. Researches in the scanning electron microscope by the use of EBSD technique of the distribution of the average equivalent to the diameter of grain and the distribution of a grain shape of selected elements of the welded joint of membrane walls of the evaporator collector with supercritical working parameters made of 7CrMoVTiB10-10 steel

The characteristic chosen examples of obtained unmelted gap between the tube and the flat bar l_n and unmelted tube thickness g_{npt} and fillet welded joints of gas-tight water walls made of 7CrMoVTiB10-10 steel are shown in Figure 8.

Figure 8a shows fillet weld joints with complete joint penetration and in Figure 8b with the gap larger than the maximum allowable one. However, Figure 9 shows the effects of the forms of revealed cracks in the weld with the gap left between the tube and the flat bar. Crack initiation occurred in the left side at side surface of the likely discontinuities arising in this area during its calibration. The initiation and crack growth is directly related to the resulting lamellar structure of the lower bainite with martensite or martensite with hardness characterized by a high level of internal stresses.

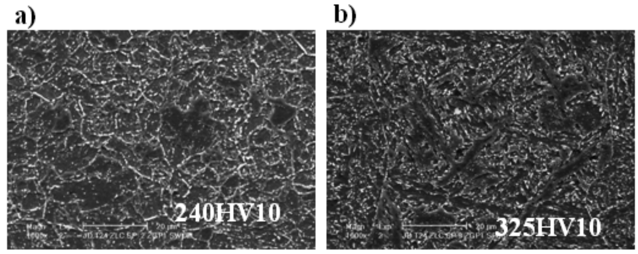

Fig. 7 The types of microstructure of the heat affected zone of welded joints in gas-tight welds of water walls made of 7CrMoVTiB10-10 steel, depending on the temperature of preheating before welding and after welding cooling speed

a) granular bainite with fine precipitates,
b) lamellar microstructure of lower bainite with martensite

6. The effect of joint penetration on the crack sensibility of fillet welds of membrane walls

Depending on the geometrical dimensions of tubes and the flat bars as well as the side surface of the flat bar after calibration welded joints can be achieved with total joint penetration or with left gap between the tube and the flat bar.

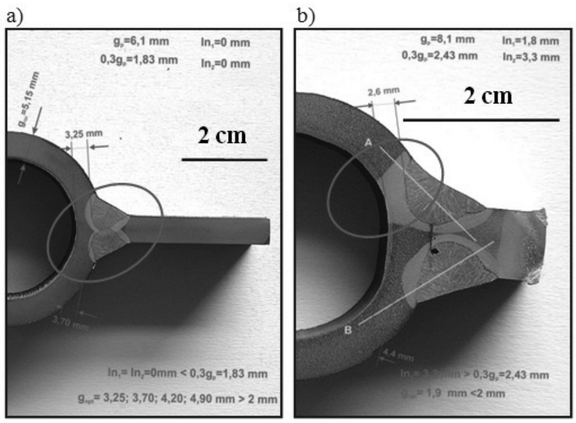

Fig. 8. Examples of obtained size of the unmelted gap between the tube and the flat bar l_n and unmelted thickness of the tube g_{npt} thickness of fillet welded joints of gas-tight water walls made of 7CrMoVTiB10-10 steel, depending on real conditions and welding parameters:

a) l_n=0; g_{npt}=3.25; ($g_{r\ rz}$=5.51 mm; $g_{p\ rz}$=6.10 mm);
b) narrow HAZ
c) l_n=3.3 mm; g_{npt} = 2.60; ($g_{r\ rz}$=5.51 mm; $g_{r\ rz}$=8.10 mm);
d) HAZ on the entire thickness of the tube

The effect on the level of internal stresses in the elements of the welded joint may also have structure of the tube material and the lower flat bar being a mixture of lower bainite with martensite, which in investigated 7CrMoVTiB10-10 steel often arises. Thus, the occurrence of discontinuities in the elements of the welds with such microstructure may cause initiation and development of cracks.

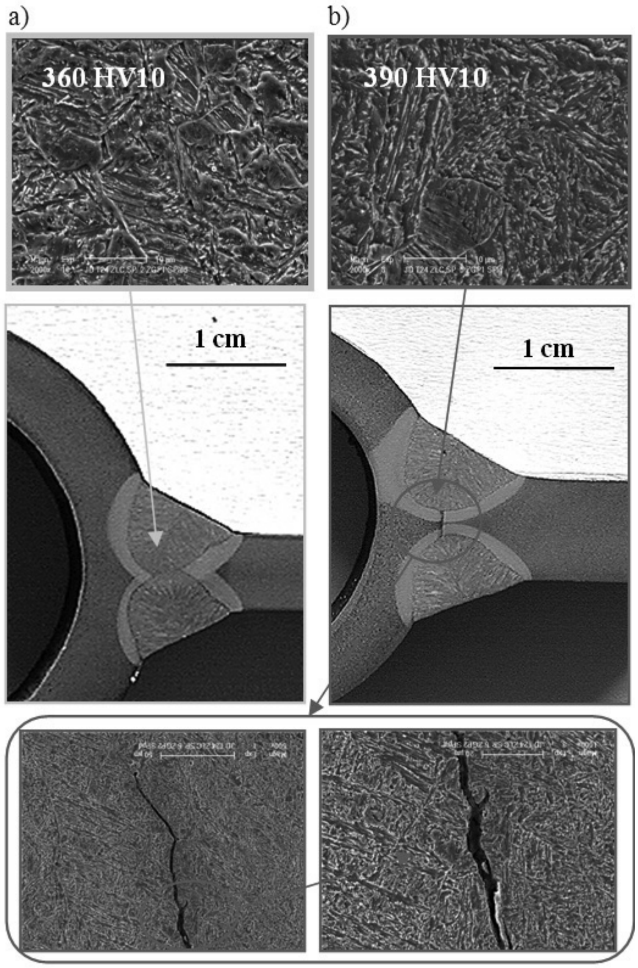

Fig. 9. Comparison of crack sensibility of obtained fillet welded joints of gas-tight water walls made of 7CrMoVTiB10-10 steel with various degrees of joint penetration of various sizes of HAZ and various forms of martensite of weld material
a) thick-lath martensite with hardness of ca. 340-360 HV10,
b) fine-lath martensite with hardness min. 390 HV10

7. Peripheral welded joints of tubes of gas-tight water walls

Another problem is the technology of the peripheral welded joints of membrane wall tubes. They are made by TIG method. As in the case of fillet welds the state of the microstructure of the tube material is not without significance. Lamellar microstructure appearing in it being very often a mixture of lower bainite with martensite can have a significant impact on the level of internal stresses in the made peripheral welded joints. Also applied welding materials that are chemically related to welded 7CrMoVTiB10-10 steel cause most often appearance of the structure in the weld being fine-lath martensite with high hardness.

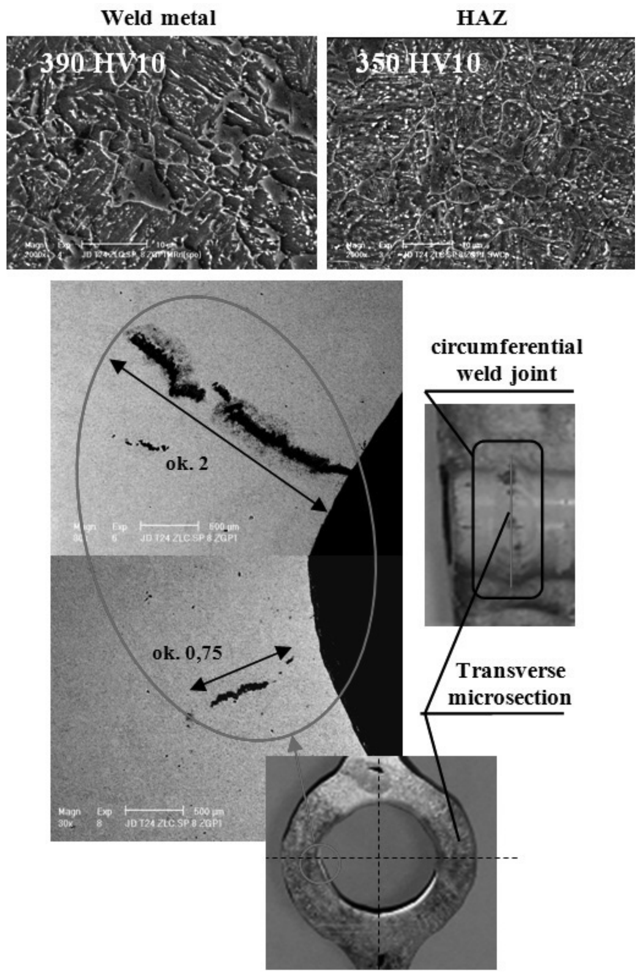

Fig. 10. Cracks in the peripheral welds of welded joints of the inner surface side in the direction perpendicular to the tube axis of the gas-tight tubular wall of 7CrMoVTiB10-10 steel

Then a high level of internal stresses requiring immediate application of relaxing heat treatment, normally used for steel with tempered martensite structure. Its absence causes the release of those stresses by creating cracks. Those welds have a tendency to crack initiation and development of the inner surface of the side surface of tubes. It creates an additional problem. Their disclosure by standard ultrasonic methods is impossible due to the geometrical dimensions of the welds and the tubes. The only method that allows them to disclose are radiographic examination. However, they have limited application and are not suitable for widespread application. The example of disclosed cracks in the weld of the circumferential tube made of 7CrMoVTiB10-10 steel in a tranverse microsection made by the circumferential weld is shown in Figure 10.

Cracks are arranged perpendicularly to the tube axis and their initiation and propagation occurred from the inner surface of the tube. Their depth up to ca. 2 mm causes that an undamaged part of the tubular wall thickness is less than the required computational one g_o what results in loss of the ability of the element to transfer the required computational load for the computational parameters.

8. Proposals enabling to lessen or eliminate the tendency to crack welded joints of membrane walls of the evaporator collector

It is assumed that material is well-weldable when the equivalent $C_e \leq 0.45$ and then there is no tendency to cold cracking. When the value of $C_e>0.45$ then this tendency increases, although it is not the only element that decides about it. The impact has also the level of hardness in HAZ and the weld and parameter P_{cm} of tendency to brittleness associated with the phase transitions. The impact values of P_{cm}, however, is closely associated with the level of preheating temperature before welding. Those elements should therefore be analyzed together.

In Table 2 the obtained values of the equivalent C_e and parameter P_{cm} for the analyzed materials of the tubes and the flat bars made of 7CrMoVTiB10-10 steel with different structures from being a mixture of granular bainite and bainite to being a mixture of lower bainite with martensite are presented. When the chemical equivalent of carbon C_e for the examined steel equals ca. 0.9 and more, while parameter P_{cm} tendency to brittleness associated with the phase transitions is above ca. 0.34, the appearance of lower bainite with martensite can be expected. However, when the temperature level of preheating before welding is too low then yet that tendency may reveal for the material with chemical composition, which corresponds to the lower value of the parameter P_{cm} [31,32].

Another more difficult problem to solve was the transportation of segments made in industrial conditions to a building site, their joining during the assembly and conducting necessary repairs. Pre-selecting material of tubes and flat bars, as well as materials for welding in strict compliance with parameters and rules of subsequent steps in technological processes of their production may allow to achieve segments of membrane walls with less crack sensibility. In industrial conditions, however, it is impractical and impossible to overcome or avoid those problems, it is necessary to seek other solutions.

The first proposal of another solution is the application to the production of fillet joints of welded materials having chemical composition close to the low-alloy steel of two-component type of 13CrMo4-5 or 10CrMo9-10 or while using flat bars of those steels. It gives a chance to receive a fillet weld with hardness not exceeding 350 HV10, and often probably even much less. Such a solution provides transfer of load of the pressure and temperature of the medium flowing through the boiler tubes.

Table 2.
Ratios of weldability of examined tubes and flat bars of 7CrMoVTiB10 low-alloy steel for selected types of microstructure dependent on the chemical composition of steel and the cooling speed

No	Microstructure		Chemical equivalent of carbon C_e	Fracture sensitivity parameter associated with the phase transitions P_{cm}
	Type of structure	Phase components in the structure; granular bainite/ bainite/ martensite, %		
		TUBES		
1	granular bainite and bainite	65/35/0	0,8580	0.2928
2	**lower bainite with martensite**	**0/75/25**	**0.9497**	**0.3650**
		FLAT BARS		
3	granular bainite and bainite	65/35/0	0.8884	0.3171
4	**lower bainite with martensite**	**0/69/31**	**0.9084**	**0.3445**

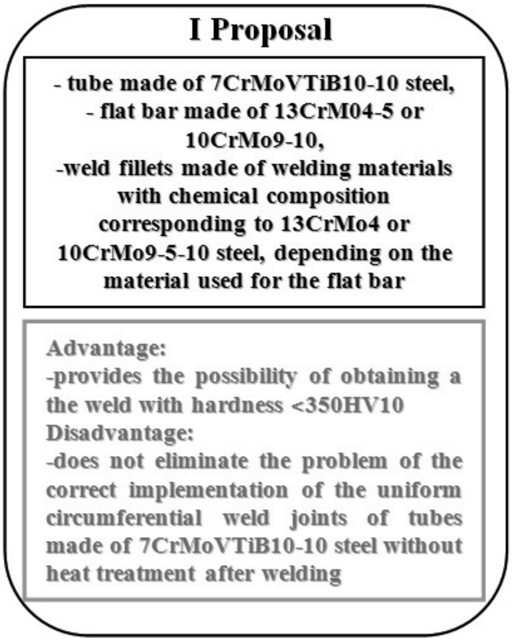

Fig. 11. Proposal of the application of tubes made of 7CrMoVTiB10-10 and flat bars made of 13CrMo4 or 10CrMo9-5-10 steel and welding materials of similar chemical composition

However, the chemical composition and properties of the weld material and the flat bar ensure a transfer of loads from the weight of its own structure and the level of temperature and chemical composition of the exhaust gas acting on the inner structure of the evaporator collector. It does not eliminate the problem with making butt welds of tubes made of

7CrMoVTiB10-10 steel and their crack sensibility by the use of those joints without heat treatment after welding (Fig. 11)

Another proposal could be an attempt to design and manufacture a combustion chamber consisting of a gas-tight tubular wall segments made of different materials, depending on the prevailing temperature and stress in the given area of the chamber. Then only the most loaded elements of steel were achieved out of 7CrMoVTiB10-10 steel, and the other with the previously known and tested 13CrMo4-5 and/or 10CrMo9-10 low-alloy steels.

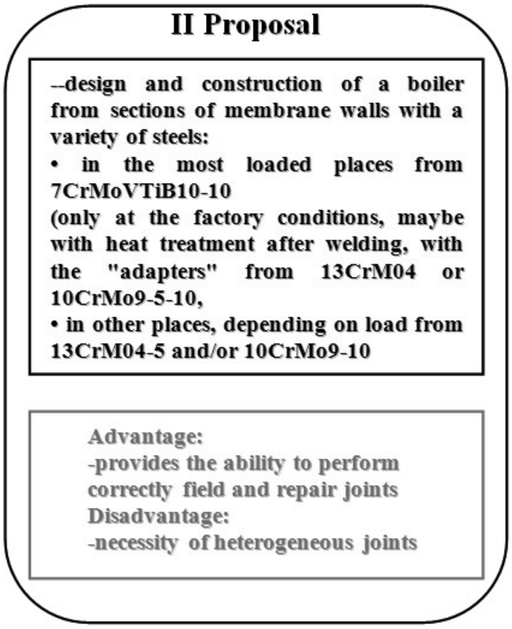

Fig. 12. Proposal of the application of tubes and flat bars made of 7CrMoVTiB10-10 steel on segments of membrane wall made only at the factory with "adapters" 13CrMo4-5 and/or 10CrMo9-10 steel for field assembly. In other places, depending on the load segments made of 13CrMo4-5 and/or 10CrMo9-10 steel

Elements of 7CrMoVTiB10-10 steel would be done only at the factory with "adapters" out of 13CrMo4-5 or 10CrMo9-10 steel, or in places where their joining at the assembly. A limited number of segments of 7CrMoVTiB10-10 steel enable their performance with more stringent requirements and of material selection, the technological process of their manufacturing, and in the extreme case of performing heat treatment after welding (Fig. 12).

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It is necessary also to consider the use of a new type of steel with the chemical composition enriched with elements that block the formation of lamellar structures of lower bainite with martensite. Probably the similar chemical composition would be characterized by welding materials. Such material is likely to be characterized by slightly lower basic strength properties and slightly lower creep resistance compared to 7CrMoVTiB10-10 steel. Those properties are, however, higher than owned by the previously used traditional two-component low-alloy steels of Cr-Mo type, which should allow its use for parts of boilers with supercritical working parameters (Fig. 13).

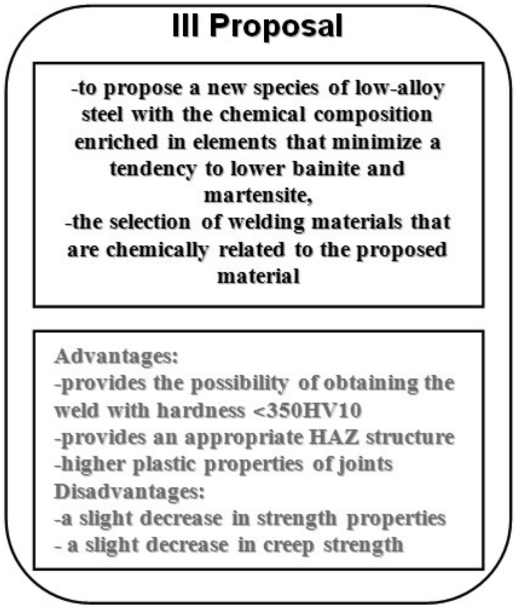

Fig. 13. Proposal of the application of a new use of new species of low-alloy steel with the chemical composition enriched in elements that minimize a tendency to lower bainite and martensite

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