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Robotic CMT arc braze welding of 10CrMo9-10 steel tubes with internal copper lining

Abstract: The article presents issues related to arc braze welding of tubes made of 10CrMo9-10 (10H2M) boiler steel lined inside with copper. In addition, the study points to possibilities of producing joints using conventional and innovative welding methods as well as presents results of radiographic, metallographic and mechanical tests (static tensile test, technological bending test, hardness measurements) of braze welded joints made using a robotic braze welding stand and the CMT (Cold Metal Transfer) method.

Keywords: braze welding, robotic welding, steel 10CrMo9-10, copper lining

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Introduction

Technological and economic development combined with growing demand for innovative, reliable equipment characterised by high aesthetics and workmanship necessitate the improvement of production processes, including those directly related to joining technologies. In addition, growing environmental and economic awareness of societies force manufacturers to use advanced structural materials and join them in various material configurations in order to obtain desired functional and operational properties [1, 2]. It should be noted that in addition to the pursuit of environmental advantages and mankind's incessant attempts at overcoming new barriers, e.g. related to speed, height, length, range etc., various ambitions, (sometimes exorbitant) of designer engineers also play an important role. The above-named goals and ambitions cannot be met without the possibility of joining materials characterised by different physico-chemical and mechanical properties, which is often difficult and requires the improvement of existing joining technologies or the development of new techniques. Primary difficulties accompanying the joining of dissimilar materials are of metallurgical nature and can be encountered in welding processes involving the stirring of base material and filler metal components (so-called fusion welding) [3-6]. The aforesaid problems are also present when bonding copper with steel, the joints of which are widely used in various industries, e.g. in refrigerating or heating systems, boilers, household equipment, structures fabricated for the chemical, ship-building and metallurgical

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industries as well as when making windings of high-power generator stators [1-6].

When joining copper with steel, in addition to significant differences in the thermal conductivity of both materials (nearly 26-times higher in terms of copper) and the presence of oxides characterised by various melting points and chemical stability, the most important issue is related to the limited solubility of copper in steel [1-6]. The maximum solubility of copper at a high temperature is as follows: in iron δ – 6.5%, iron γ – 8% and in iron α – 1.4% by weight. [7]. At room temperature, in the conditions of phase equilibrium (Fig. 1), the solubility of copper in iron is limited to a mere 0.3% [8]. This is of particular importance as the PN-EN ISO 6520-1:2009 standard does not allow (in relation to any quality level, i.e. B, C and D) copper inclusions in the steel weld, making it problematic to perform welding with deep penetration and involving the use of a copper backing strip. However, there is one factor favouring the possibility of joining the aforesaid metals, i.e. the fact that they are characterised by similar linear expansion coefficients, reducing the risk of stress generation and crack formation during the cooling of the joints [1,2].

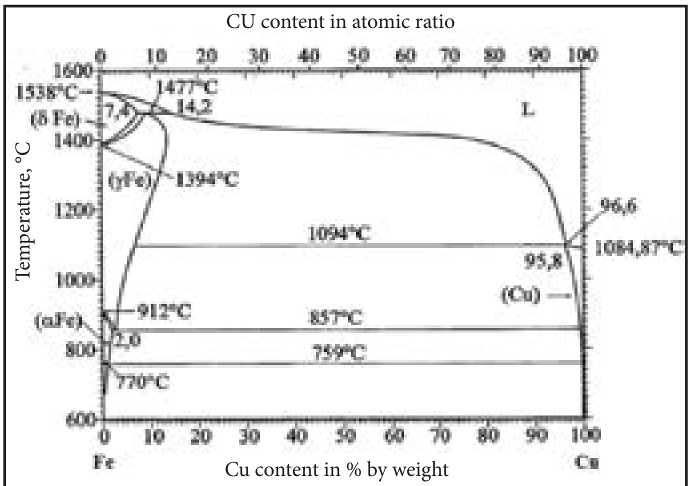

Fig. 1. Cu-Fe phase equilibrium system [8]

A copper content of above 3% by weight in the austenitic chromium-nickel alloy could trigger hot cracking [7]. The foregoing problem could be illustrated by transverse cracks in austenitic steel and the significant stirring of copper with steel (Fig. 2) accompanying the failure affecting the winding in a high-power generator stator. An electric short circuit resulted in the welding of copper wires with the tubes made of austenitic chromium-nickel steel (used for the transport of water cooling the current conduits) [2, 9]. Because of this, the use of conventional commonly applied arc welding methods, i.e. MIG and TIG, is limited. Alternatives to the conventional methods are new low-energy variants of GMA welding, i.e. ColdArc, STT, CMT etc., with synergic lines intended for braze welding processes [10-14]. Braze welding significantly reduces the formation of hot cracks as the process is not accompanied by the partial melting (or accompanied by significantly reduced partial melting) of materials being joined and the stirring of their components with the filler metal. In addition, in the aforesaid process the joint is obtained in the manner similar to the brazing (less frequently soldering) process, i.e. primarily as a result of wetting and diffusion phenomena [13, 14]. The manner in which materials are prepared for the braze welding process is different from that used in relation to the brazing process and identical as the one applied in welding processes, i.e. without the characteristic brazing gap of capillary properties [14].

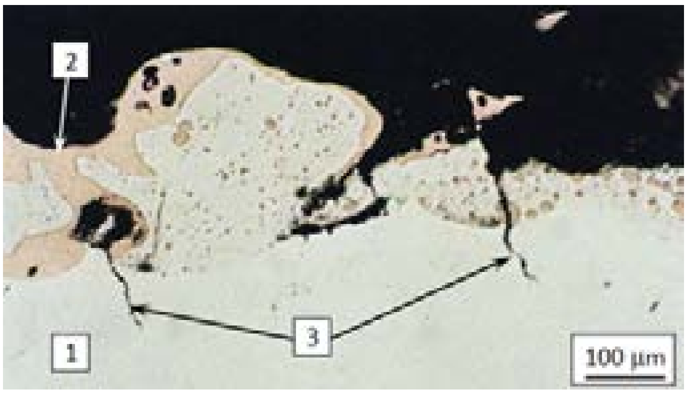

Fig. 2. Joint of copper and steel obtained using electric arc: 1- austenitic steel (1H18N9T), 2- copper Cu-ETP, 3- cracks [2,9]

Base materials and filler metals used in the tests

The base material subjected to the tests, the result of which are presented in the remainder of the article, was a tube made of steel 10CrMo9-10 (1.7380), having an internal diameter of 101.6 mm. The tube wall thickness amounted to 15.5 mm, whereas the thickness of the internal copper lining amounted to 2 mm (Fig. 3). In operating conditions (of the chemical industry) the above-presented tube is exposed to a temperature of 550°C and a pressure of 40 bars. The internal copper lining is used to protect the steel tube against the corrosive activity of aggressive media.

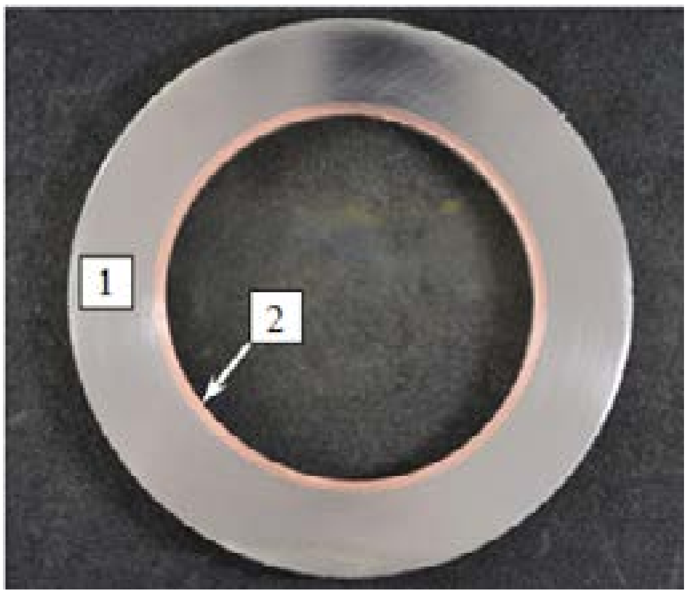

Fig. 3. Tube made of steel 10CrMo9-10 (1) lined inside with copper Cu-ETP (2)

According to the PN-EN 10216-2:2014-02 standard, steel grade 10CrMo9-10 belongs to the group of medium-alloy chromium-molybdenum steels containing the pearlitic structure. The above-named steel is creep-resistant and intended for operation at a temperature not exceeding 580°C. Because of its properties and applications, the steel is often referred to as boiler (creep-resisting) steel. The primary applications of the steel include steam boilers, steam turbines, pressure equipment, machinery elements of critical importance, rotor shafts, bolts etc. Copper Cu-ETP, lining the steel tube inside, is classified as (cathode-melted) oxygen copper (electrolytic tough pitch copper) containing the controlled amount of oxygen (copper oxide). The above-named copper is characterised by very high thermal and electric conductivity, high corrosion resistance in various environment and resistance to the effect of most factors excluding those containing ammonia. The aforesaid copper grade is also extensively used in the electric industry, in sanitary systems and in the automotive industry [17].

The selection of welding consumables to be used in the braze welding process is difficult because of the specific nature of the process, where, by definition, materials to be joined should not be partially melted but only wetted by the filler metal and where materials to be joined should be bonded as a result of diffusive mechanisms. The lack of penetration, characteristic of the braze welding process, makes it possible to avoid metallurgical problems related to the stirring of the filler metal with the base material [14]. The most important issue is the adjustment of a filler metal to the braze welding of dissimilar materials. Usually, the filler metal is selected by adjusting its melting point to the base material characterised by a lower melting point [13,14]. In cases of the slight gradient between the melting point of the filler metal and that of the base material, it is not always possible to avoid the partial melting of the edges of the material having the lower melting point [14]. The braze welding of the tube made of

Table 1. Chemical compositions of the joined materials and filler metal [16-18]

Material	**Chemical composition, % by weight**													
	C	**Mo**	**Si**	**Mn**	**Cr**	**Ni**	**P**	**S**	**Fe**	**Cu**	**B**	**O**	**Pb**	**Sn**	**Zn**
Cu-ETP	-	-	-	-	-	-	-	-	-	rest	0.0005	0.04	0.005	-	-
10CrMo9-10	0.08 ÷ 0.15	0.9 ÷ 1.1	0.15 ÷ 0.50	0.4 ÷ 0.6	2.0 ÷ 2.5	<0.3	<0.03	<0.03	rest	<0.25	-	-	-	-	-
CuSi3	-	-	<3.0	<1.0	-	-	-	-	0.07	rest	-	-	-	<0.1	<0.1

steel 10CrMo9-10, lined with copper inside, was performed using silicon bronze CuSi3 in the form of a wire having a diameter of 1.0 mm. The chemical compositions of the base materials and of the filler metal are presented in Table 1 [16-18]. The braze welding process was shielded using pure Argon 4.5 (99.995% Ar).

Boiler steel 10CrMo9-10 having a wall thickness of up to 16 mm is characterised by the following mechanical properties [16]:

– tensile strength R_m – 480 ÷ 630 MPa,
– conventional yield point $R_{p0,2}$ – max. 310 MPa,
– impact energy KV, in 20°C – max. 31 J,
– hardness – max. 130 HV,
– elongation – max. 18%.

CMT braze welding of tubes

The joining of dissimilar materials entails various problems potentially affecting the quality and mechanical properties of joints. The braze welding technology is usually used to make overlap joints (because of their adhesive-diffusive nature). However, the above remark is primarily concerned with thin-walled elements (sheets). When joining materials of significant thicknesses (as in the case under discussion), the edges of such materials are prepared for braze welding in the same manner as that applied in preparation preceding the welding process, i.e. involving the use of scarfing and butt arrangement (Fig. 4).

Because of the fact that the tests were the first attempts aimed to develop a technology enabling the joining of tubes made of boiler steel with internal copper lining, the tubes were not braze welded around the entire circumference but were cut across into four equal parts, i.e. 90 mm long quadrants. Afterwards, before the performance of braze welding tests, copper (run-on and run-off) sheets were TIG-welded to the specimens (Fig. 5).

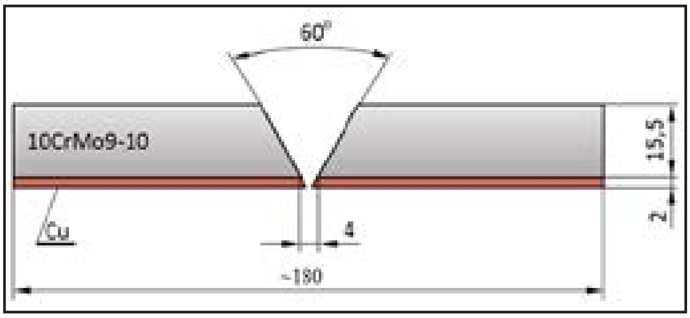

Fig. 4. Preparation of the edges of the tube made of steel 10CrMo9-10 (lined with copper inside) for the process of braze welding

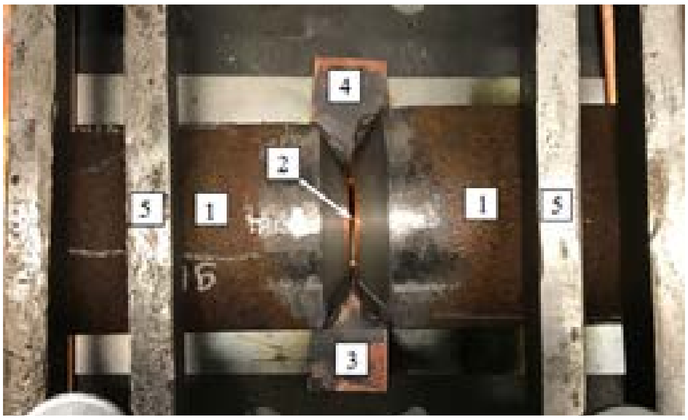

Fig. 5. Preparation of specimens for braze welding: 1- tube made of steel 10CrMo9-10, 2- lining made of Cu, 3- run-on sheet, 4- run-off sheet, 5- fixing clamp

The braze welding process was performed using a robotic station and the CMT (low-energy) method. The station was equipped with a Fronius TransPuls Synergic 3200 synergic welding power source featuring the digital control of welding current, a system tasked with the reversing of the filler metal wire when detecting a short circuit (minimising the amount of spatters) and a digitally controlled Fronius VR 7000-CMT 4R/G/W/F++ filler metal wire feeder. During the process, the working movements were performed by a Kawasaki BA series robot provided with a Robacta Drive CMT PAPW welding torch, equipped with an internal digitally controlled asynchronous AC motor enabling the fast reversing of the filler metal wire to a special buffer [19].

The adjustment of braze welding process parameters was performed using 2 mm thick copper sheets. The process was started by adjusting parameters entered in the synergic line in relation to filler metal CuSi3 and copper as the base material of a predefined thickness. Afterwards, the parameters were corrected by changing the welding rate. The initial tests revealed that the process required the very precise adjustment of technological parameters, the change of which, even within a very narrow range, reduced the process stability and led to the formation of numerous welding imperfections in the joints. Even slight changes in the parameters were responsible for the formation of spatters resulting from the reduced process stability, the lack of wettability and incomplete fusions or the excessive partial melting (melt-through) of copper edges. The ultimate CMT braze welding process parameters, for which two test joints (no. 1 and 2) were made, are presented in Table 2. The weld groove was filled completely by 15 beads. Once the joints had been made, run-on and run-off sheets were cut out of them in order to sample specimens for macro and microscopic metallographic tests and mechanical tests.

Table 2. Parameters used in the braze welding of the tube made of steel 10CrMo9-10 lined inside with copper

No.	Parameter	Value
1.	Current, I_S	178 A
2.	Arc voltage, U	18 V
3.	Filler metal wire feeding rate, V_d	10.8 m/min
4.	Welding rate, V_s	60 cm/min
5.	Electrode extension, L_w	15 mm
6.	Gas flow rate, Q	16 dm^3/min

Radiographic and macro and microscopic metallographic tests

The test joints were first subjected to radiographic tests (RT) performed following the requirements of the PN-EN ISO 17636-1:2013-06 [20] and PN-EN 12799:2003/A1:2005 [21] standards. The radiographs did not reveal the presence of internal welding imperfections in the brazewelds. An exemplary radiograph is presented in Figure 6.

Figure 7 reveals that the joints were made properly and were free from welding imperfections in the macroscale. It was possible to notice the bonding imperfection (4) of the copper tube (2) constituting the internal lining along the length of the tube made of steel 10CrMo9-10 (1). The copper tube was forced

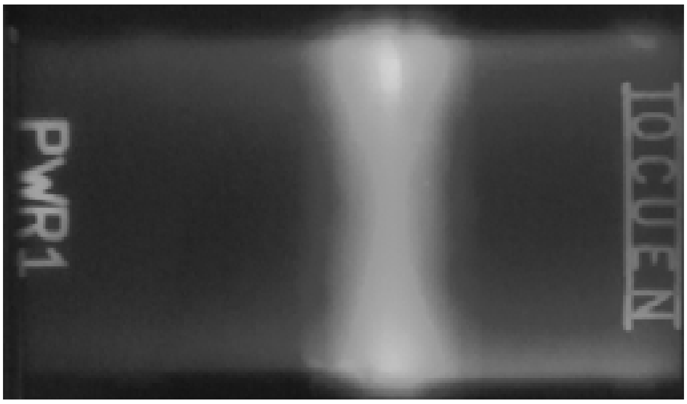

Fig. 6. Exemplary radiograph (negative) of the braze welded joint made of steel 10CrMo9-10 with internal copper lining

into the steel tube and the joint was created only where the individual sections of the tubes were joined on the circumference. It was also possible to notice a slight change in the geometry of the weld groove, particularly near the root and face of the weld (A, B), indicating the slight partial melting of the steel during the braze welding process. Because of the fact that braze welded joints are assessed in the same manner as brazed joints, i.e. in accordance with the PN-EN ISO 18279:2008 standard [22], the above named imperfection was designated as imperfection 7UAAC of group VI *Miscellaneous imperfections*, i.e. the excessive reaction of the filler metal with the base material. In cases of dissimilar joints, particularly in terms of steel and copper, it could be important which of the materials undergoes partial melting. Because of the fact that, in terms of the chemical composition, the filler metal was similar to the copper lining, it would be more favourable for copper to be partly melted as the partial melting of the steel could result in the formation of hot cracks as a result of the diffusion of copper from the filler metal to the steel on grain boundaries. The above-presented issue was discussed in publications [4, 23]. The formation of hot cracks could also be favoured by the fast discharge of heat from the joint area by the copper lining, increasing tensile stresses in the steel and facilitating the diffusion of copper from the weld deposit on grain boundaries. In the case under discussion no cracks were detected in the macroscale.

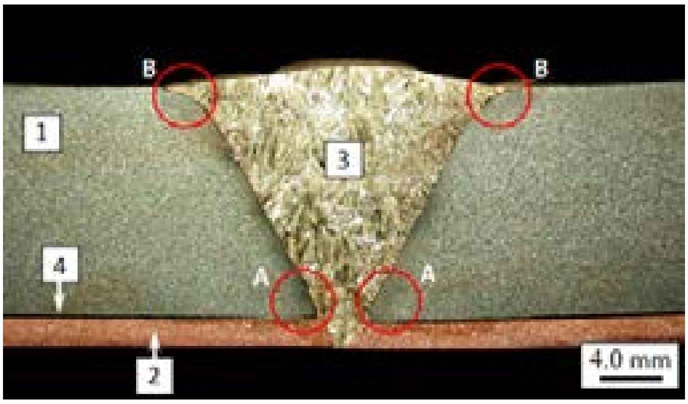

Fig. 7. Macrostructure of welded joint no. 1 of the tube made of steel 10CrMo9-10 lined with copper (2): brazeweld (3), bonding imperfection between the steel and the lining along the tube length (4), partial melting of the steel (A, B); etchant: Mi1Fe and Mi19Cu

making the bead on the left, the base material was heated to a higher temperature, favouring the occurrence of mechanisms responsible for the formation of the reactive zone as a result of the partial melting of the steel. The partial melting of the steel was also manifested by slight inclusions in the brazeweld structure, the greater amount of which could also be observed on the left side of the joint, characterised by the greater width of the reactive zone. It was also possible to notice that the width of the heat affected zone (HAZ) was significantly narrower in comparison with the welded joints and did not exceed 20 μm.

The microscopic tests were performed in various areas of the joint and base materials. Examples of microstructures are presented in Figures 8 and 9. Because of the fact that braze welded joints were formed as a result of diffusive mechanisms, their functionality and mechanical properties were primarily dependent on the quality of the bonding at the interface between the brazeweld and steel 10CrMo9-10. On the face side, both on the left and right side of the joint, at the interface, it was possible to notice a reactive zone of a varied width, formed as a result of the partial melting of the steel. On the left side of the joint, the width of the reactive zone was approximately 4 times greater (10÷15 μm) than on the opposite side (Fig. 8). This was triggered by the position of the welding torch (electrode tip) in relation to the edge of the weld grove and/or the braze welding sequence as the first bead to be made was on the right. The foregoing was responsible for the fact that when

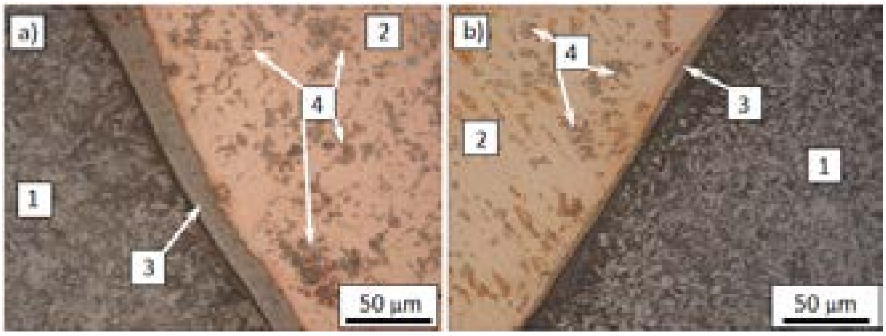

Fig. 8. Microstructure of welded joint no. 1 at the interface of the joint of the tube made of steel 10CrMo9-10 with the brazeweld (2): a) left side of the joint, b) right side of the joint; 3- reactive zone , 4- steel inclusions in the brazeweld; etchant: Mi1Fe and Mi19Cu

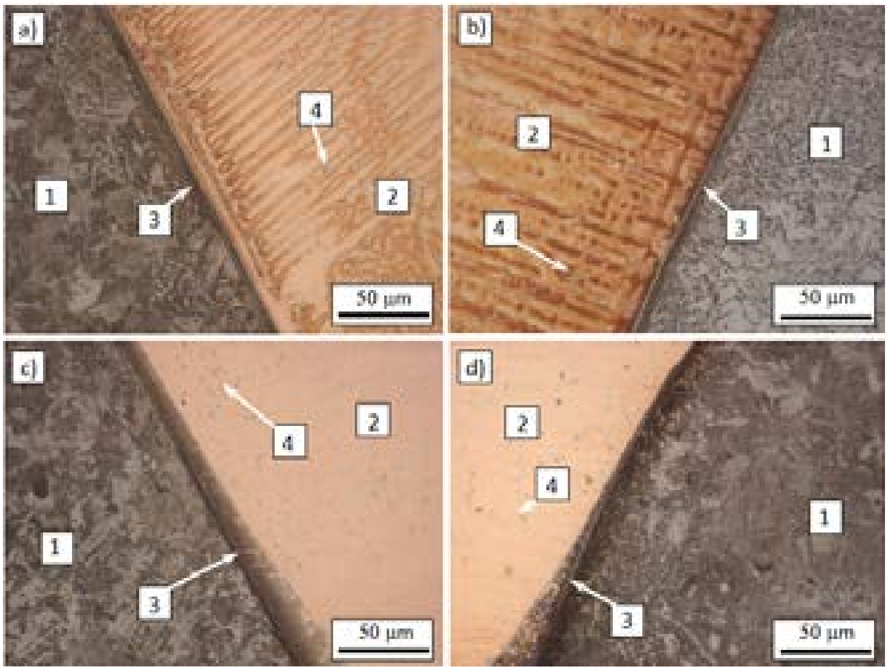

Fig. 9. Microstructure of welded joint no. 1 at the interface of the joint of the tube made of steel 10CrMo9-10 (1) with the brazeweld (2): a) central part of the left side of the joint, b) central part of the right side of the joint, c) left side of the joint near the root, d) right side of the joint near the root; 3 – reactive zone, 4 – steel inclusions in the brazeweld; etchant: Mi1Fe and Mi19Cu

In the central part of joint no. 2, at the interface of the steel 10CrMo9-10 and the brazeweld, the width of the reactive zone was comparable on both sides and did not exceed 5 µm (Fig. 9a and b). The brazeweld itself contained significantly fewer steel inclusions, which indicated the significantly lower degree of partial melting in this part of the joint. In addition, in the direction of the root, it was possible to notice an increase in the width of the reactive zone and an increase in the amount of steel inclusions in the brazeweld (Fig. 9c and d). The width of the reactive zone was similar on both sides of the joint and amounted to approximately 20 µm (near the lower edge of the steel plate).

The microstructure of the base material (steel 10CrMo9-10) was characteristic of the steel grade. The ferritic-pearlitic microstructure contained variously sized grains and was characterised by slight banding density (Fig. 10a). The brazeweld microstructure contained dark acicular precipitates of phase β against the background of bright matrix α (Fig. 10b).

Tests of mechanical properties

Specimens used in the static tensile test were prepared following the guidelines of the PN-EN ISO 4136:2013-05 [24] and PN-EN 12797:2002/A1:2005 [25] standards. The 20 mm wide specimens were cut out of the braze welded joints. In their measurement part, the specimens were milled to 12 mm. The static tensile tests of the butt braze welded joints were performed using a universal hydraulically-driven testing machine. The measurement range was up to 40 kN, whereas the travel rate of the transverse beam amounted to 0.2 cm/min. The mean tensile strength of the braze welded joints amounted to 205 MPa (because of the limited amount of the test materials, mean was taken out of 2 tests). The rupture mechanism was of cohesive nature as the specimens ruptured in the brazeweld or partly in the brazeweld and in the reactive zone (Fig. 11).

The results obtained in the test were significantly superior to those obtained in relation to the joints made using the flame braze welding method (C_2H_2 – O_2) and brass covered brazing metal grade 18XFC [26] (see Figure 12). The tensile strength of the flame braze welded joints amounted to, on average, 145 MPa. The rupture mechanism was adhesive in its nature, i.e. the brazeweld ruptured from steel 10CrMo9-10 on the side surface of the groove of the scarfed tube.

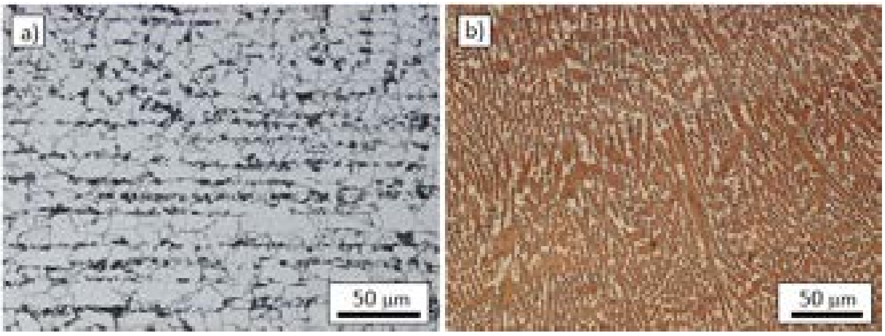

Fig. 10. Ferritic-pearlitic microstructure of steel 10CrMo9-10 (a) and the microstructure of the brazeweld made of silicon bronze CuSi3 (b); etchant: Mi1Fe and Mi19Cu

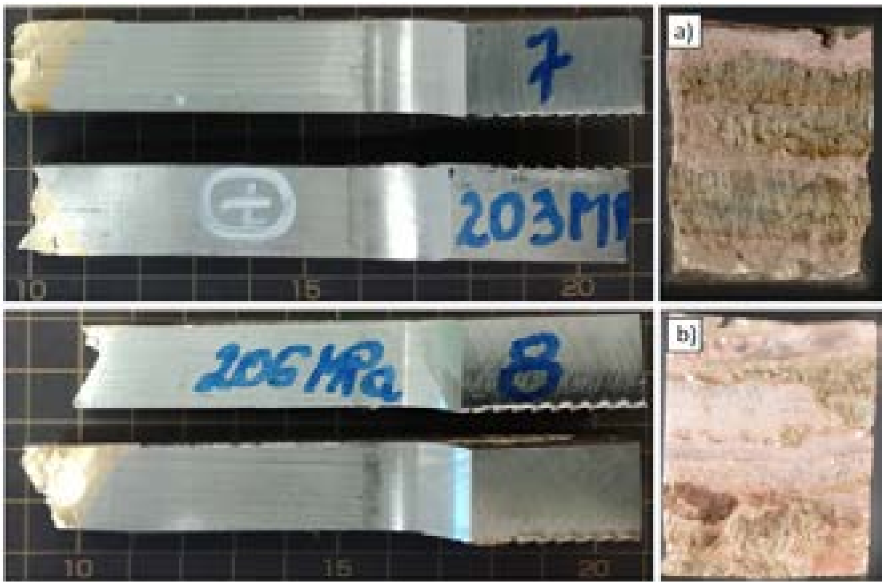

Fig. 11. Exemplary metallographic specimens of the joints after the static tensile test: cohesive rupture in the brazeweld (a) and cohesive rupture in the brazeweld and in the reactive zone (b)

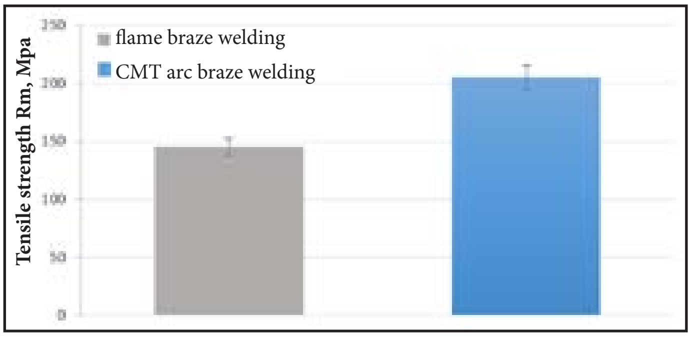

Fig. 12. Tensile strength of the braze welded joints made of steel 10CrMo9-10 lined inside with copper

The tests obtained in the technological transverse bend tests also differed significantly and revealed that better results could be obtained using the CMT arc braze welding technology (Fig. 13). The bend test was performed until the appearance of the first cracks in the joint or in its vicinity. In relation to the CMT brazed welded joints, the bend angle was four times greater and amounted to 450, which was a very good result given the significant thickness of tubes being joined and the use of the CMT arc braze welding technology.

Fig. 13. Braze welded joint made in steel 10CrMo9-10 lined with copper after the technological bend test: flame braze welding (a) and CMT arc braze welding (b)

The tests also involved the performance of hardness measurements in the braze welded joint made of steel 10CrMo9-10 lined inside with copper. The measurements were based on the Vickers hardness test under a load of 10 kG. The hardness in the base material (steel 10CrMo9-10) was restricted within the range of 157 HV 10 to 168 HV 10. The width of the heat affected zone was significantly narrower (up to approximately 20 µm) in comparison with that obtained in the welded joints. The HAZ hardness was also lower and amounted to 181 HV 10. The brazeweld made of weld deposit CuSi3 was soft; its hardness was restricted within the range of 86 HV to 92 HV 10. The hardest area in the braze welded joint was the reactive zone, the microhardness of which amounted to 491.1 HV 0.05. The softest areas was brazeweld matrix CuSi3 (134.6 HV 0.05) (see Fig 14).

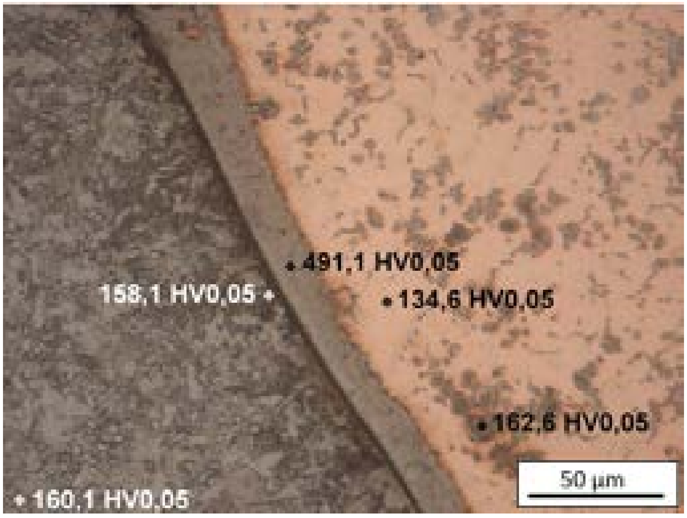

Fig. 14. Values of microhardness HV 0.05 in the braze welded joint of tube made of steel 10CrMo9-10 using filler metal CuSi3; the measured area of Figure 8a

Conclusions

The joining of copper with steel is difficult and entails numerous problems. The use of the CMT arc braze welding method when joining boiler steel 10CrMo9-10 lined inside with copper enabled the obtainment of spatter-free joints characterised by high quality and aesthetics. The joint aesthetics including both the shape and appearance of the brazeweld as well as the lack of spatters depended primarily on the selection of a joining method and the precise adjustment of process parameters. In spite of using the braze welding process, the base material (steel 10CrMo9-10) in the face and root areas was slightly partially melted. The foregoing resulted in the formation of a reactive zone, the width of which was restricted within the range of 5 μm to 20 μm. In turn, the brazeweld itself contained fine steel inclusions located primarily in the partially melted areas. The mechanical properties of the CMT arc braze welded joints were satisfactory and significantly superior to those of the flame braze welded joints. The tensile strength amounted to 205 MPa. The rupture mechanism in the brazeweld and in the reactive zone was of cohesive nature. Although the rupture took place in the brazeweld, the obtained strength was lower than that of the weld deposit (approximately 330 MPa), which could be affected by the reactive zone and steel inclusions in the brazeweld. The use of the CMT arc braze welding technology led to the more uniform distribution of stresses in the joint in comparison with that obtained using flame braze welding, minimising the risk of hot cracking of the steel as a result of the diffusion of copper from the weld deposit on grain boundaries. The hardness distribution in the braze welded joints was more uniform than in the welded joints. The foregoing was related to the significantly narrower heat affected zone and its lower hardening.

Acknowledgements

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