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# Vacuum Brazing of Dissimilar Joints Mo-SS with Cu-Mn-Ni Brazing Filler Metal

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## Abstract

The complexity of joining dissimilar materials, such as molybdenum-stainless steel, is due to the difference in thermal coefficients of linear expansion and low oxidation resistance of molybdenum. In this connection, brazing of this pair of materials should be performed in vacuum. The selection of chemical composition of brazing filler metal and its melting temperature range is very important. This work presents the results of metallographic and micro X-Ray spectral analysis investigations of dissimilar brazed joints of molybdenum-stainless steel and shows the features of the formation of brazed seams at application of brazing filler metals of Cu-Mn-Ni(Me) system. It is found that at brazed seam, crystallize reaction layers form the side of molybdenum. One layer is based on molybdenum, enriched in iron and silicon. The second layer is based on iron, enriched in silicon. At brazing temperature of 1100°C, base metal dispersion occurs, which can be avoided at temperature lowering to 1084°C. The structure of solid solution with a small amount of iron-enriched dispersed phase crystallizes in the central zone of brazed seams. The brazed joints produced with application of brazing filler metal based on Cu-Mn-Ni system are characterized by maximum values of shear strength.

**Keywords:** brazing, microstructure, brazing filler metal, molybdenum, stainless steel, micro X-ray spectral analysis, shear strength

## 1. Introduction

At present materials which are difficult to join by traditional welding methods are widely applied in different industries. These, primarily, are dissimilar materials, for joining which brazing is extensively used. This method of material joining has been known since ancient times, it is developing continuously, and the area of its application becomes wider. Producing permanent joints of a refractory material—molybdenum with stainless steel by brazing is highly important for many industries, related to structure operation at high temperatures. This is due to high melting temperature, high modulus of elasticity, relatively low density, and excellent specific strength of molybdenum at high temperatures. Recrystallization temperature and mechanical properties of molybdenum depend on many factors and, primarily, on the degree of its purity, method of its production, as it is sensitive to interstitial impurities. Recrystallization temperature of unalloyed molybdenum is in the range of 900–1000°C. It depends on metal purity, temperature, degree of deformation, and

recrystallization duration [1]. Molybdenum becomes brittle after recrystallization, so that the melting temperature range of brazing filler metal is important at its selection.

Joining dissimilar materials is a more complex task than joining similar materials. The complexity of joining dissimilar materials is due to a significant difference in thermal coefficients of linear expansion (TCLE) and low oxidation resistance of molybdenum. So, at a temperature exceeding 500°C, the sublimation of  $\text{MO}_3$  oxide begins on molybdenum surface. It becomes significant at the temperature of 600°C. At further temperature increase above 800°C, this oxide melts, leading to superactive oxidation of molybdenum in a standard atmosphere [1]. In this connection, it is better to conduct molybdenum brazing in a vacuum. Vacuum brazing has several advantages, compared to the traditional methods of brazing in an air atmosphere. In a vacuum furnace atmosphere, a practically complete absence of any substances is achieved. The most important feature of vacuum brazing is the possibility of conducting the process without the application of fluxes. In addition to eliminating the operation of flux washing, it allows producing joints with high strength, corrosion resistance, and vacuum tightness, which is very important for the fabrication of many structures.

In brazing dissimilar materials, an important task is a correct selection of the chemical composition of brazing filler metal, its solidus, and liquidus temperature. Vacuum brazing of stainless steels is usually performed in the temperature range of 1000–1200°C. This is the temperature range of quenching of most alloy steels, which allows you to combine brazing with heat treatment of the material and thereby achieve high strength brazed joints. The brazing filler metal should readily wet the materials being brazed, it should be sufficiently strong and, at the same time, ductile, should readily deform, and promote relaxation of stresses, arising during brazing and cooling to room temperature.

The authors of [2] presented the problems that arise when brazing dissimilar materials. We focused on the difference in the coefficients of thermal expansion of brazing filler metal and base metals, which can lead to the appearance of internal stresses, as well as to deformations of the base metal.

In various industries, brazing filler metal based on nickel and copper are widely used: VPR1, VPR4, BNi-1, BNi-2, BNi-3, BNi-4, BNi-5, BNi-7, BNi-8, etc. [3–10]. They are used for brazing steels of various grades, heat-resistant nickel alloys, and many other materials. As a rule, these brazing filler metals contain Si and B as depressants (**Table 1**), which provide an acceptable temperature range for melting and good wetting of the brazed metals.

The disadvantages of these brazing filler metal include active diffusion of boron, the formation of fusible boride, and silicide phases that are released in brazing joints (**Figure 1(a)**) and in the base metal during brazing (**Figure 1(b)**).

They relate to brittle intermetallic compounds that adversely affect the performance of brazed joints during prolonged use.

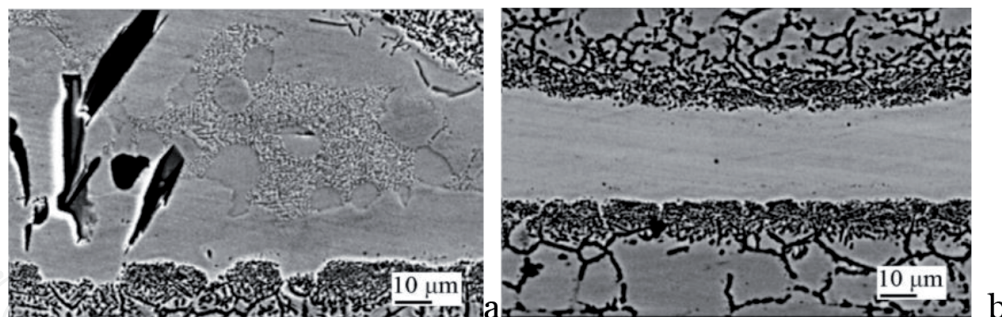
Brazed joints obtained using BNi-2, BNi-3, and BNi-4 brazing filler metal consist of three phases [9]: a nickel-based solid solution adjacent to the base metal and located in the center of the brazed joint of nickel borides and eutectic consisting of nickel silicides and borides.

Boron actively diffuses into stainless steel adjacent to the seam. In the process of brazing at high temperature, it forms intermetallic boride phases along grain boundaries. When these phases are in large numbers, they reduce the fatigue strength and corrosion resistance of steel. The brittle phases determine the brittleness of the joint as a whole, and crack development occurs along these phases. It is possible to increase the strength of brazed joints by forming a structure of a solid solution in the brazed seams, which effectively inhibits the development of cracks. Rabinkin has extensively studied the problems associated with the presence of

Grade of BFM	Chemical composition of the main elements, % (wt.)						
	Cr	B	Si	Fe	Mn	Cu	Ni
BNi-1	13.0–15.0	2.75–3.5	4.0–5.0	4.0–5.0	—	—	Base
BNi-1a	13.0–15.0	2.75–3.5	4.0–5.0	4.0–5.0	—	—	Base
BNi-2	6.0–8.0	2.75–3.5	4.0–5.0	2.5–3.5	—	—	Base
BNi-3	—	2.75–3.5	4.0–5.0	0.5	—	—	Base
BNi-4	—	1.50–2.20	3.0–4.0	1.5	—	—	Base
BNi-5	18.5–19.5	0.03	9.75–10.50	—	—	—	Base
BNi-8	—	—	6.0–8.0	—	21.5–24.5	4.0–5.0	Base
VPr1	—	0.1–0.3	1.5–2.0	0.1–1.5	—	base	27.0–30.0
VPr4*	—	0.15–0.25	—	1.0–1.5	27.0–30.0	base	28.0–30.0
VPr7	—	0.07–0.2	0.8–1.2	0.1–0.8	32–35	—	Base
VPr11**	14.0–16.0	2.0–3.0	4.0–5.0	3.5	—	—	Base

\*4.0–6.0% Co; 0.1–0.2% P  
 \*\*0.1–1.0% Al

**Table 1.**  
 Chemical composition of brazing filler metals.



**Figure 1.**  
 Microstructure of brazed joints of 1Kh18N9 steel, produced using brazing filler metal Ni-7Cr-4.5Si-3Fe-3.2B: fillet section, (a) brazed seam (b) [10].

borides in brazed joints [7]. He suggests the use of prolonged heat treatment to dissolve borides and silicides, which complicates the process of obtaining joints and does not always allow you to get rid of them [7, 8] completely.

The use of silver brazing filler metals for brazing an alloy of Mo60%-Cu40% provides shear strength in the range of 170–220 MPa [11]. The application of brazing filler metals based on Ni-Cr-Si system containing boron [12] for brazing molybdenum (Mo60%-Cu40%) with stainless steel does allow achieving a high strength—200–230 MPa.

Promising are brazing filler metals with solid solution structure, which are characterized by acceptable melting temperature and high mechanical properties and act as a damper between two dissimilar metals, which promotes relaxation of

stresses in brazed joints. The presence of solid solutions characterized alloys based on copper-nickel and copper-manganese systems [13].

The copper-manganese system has a minimum melting point (821°C) at a manganese concentration of 33.7 atom. %. With decreasing temperature, ordering processes occur in the alloys of this system, and the ordered phases Cu<sub>5</sub>Mn and Cu<sub>3</sub>Mn precipitate, increasing the strength of the solid solution. Analysis of nickel-manganese binary system is indicative of complete solubility of manganese in nickel in the liquid state at increased temperature but with temperature lowering precipitation of several phases takes place.

Proceeding from analysis of binary state diagrams of Cu-Ni, Cu-Mn, and Mn-Ni systems [13], Cu-Mn-Ni ternary system was selected as the base one [14, 15]. This system has a wide range of solid solutions. So, in the Cu-Mn-Ni alloy, additional alloying with silicon should improve the spreading of the surface of stainless steel, and alloying with iron should reduce erosion of stainless steel by brazing during the brazing process.

This work aims to study the features of the formation of the microstructure of brazed joints, the relationship between the structure, the initial composition of the brazing filler metal, and the strength of dissimilar brazed joints Mo-stainless steel obtained by vacuum brazing using brazing filler metal of the Cu-Mn-Ni system.

## 2. Experimental procedure

As the base metal, molybdenum, stainless steel 09Kh18N10, and brazing alloys based on copper-manganese system were applied. The brazing filler metal was applied in the cast form and was produced by melting in the laboratory installation in the shielding atmosphere of argon. The produced ingots were overturned and melted down (up to 5 times) in order to average the chemical composition and provide a uniform distribution of elements. The solidus and liquidus temperatures of cast brazing alloys were determined using the installation of high-temperature differential analysis in the shielding atmosphere of helium at constant heating and cooling rate (40°C/min).

Before brazing, the samples were machined and cleaned (degreased). The prepared samples were overlapped, and the brazing filler metal (**Table 1**) was placed on the surface of the base metal (near the gap) and loaded into a vacuum furnace with radiation heating to conduct capillary vacuum brazing with a rarefaction of the working space of  $1 \times 10^{-3}$  Pa.

Brazing filler metal (**Table 2**) in the cast state was placed at the gap (size of fixed brazing gap was 50 μm).

For metallographic examinations the overlapped joints were brazed, and the specimens were cut out perpendicular to the brazing seam; the microsections were manufactured according to the standard procedure and examined using the scanning electron microscope TescanMira 3 LMU.

No.	Base system of brazing filler metal alloying	Brazing temperature, °C/time, min
1	Cu-Mn-Ni-Fe-1.0Si	1050 /3
2	Cu-Mn-Ni-0.2 Si	1100 /5
3	Cu-Mn-Ni	1084 /3

**Table 2.**  
*Used brazing filler metals and brazing modes.*

The distribution of chemical elements was examined using the method of a local micro X-ray spectrum analysis applying the energy dispersion spectrometer Oxford Instruments X-max (80 mm<sup>2</sup>) under the control of the software package INCA. The locality of micro X-ray spectrum measurements did not exceed 1 mm; the film- ing of microstructures was carried out in back-scattered electrons (BSE), which allowed examining the microsections without chemical etching.

For mechanical tests, the plane overlap joints of the 100 × 30 × 3 mm size (three samples for each brazing filler metal) were brazed and tested using the installation MTS-810.

### 3. Results and discussion

#### 3.1 Microstructure of brazed joints of molybdenum with stainless steel at the application of brazing filler metal of Cu-Mn-Ni-Fe-1Si system

In vacuum brazing of dissimilar materials such as molybdenum-stainless steel by brazing filler metal of Cu-Mn-Ni-Fe-1Si [16] system, good wetting of both the materials is observed, namely, molybdenum and stainless steel. This ensures the formation of smooth and tight fillets (**Figure 2(a)** and **(b)**).

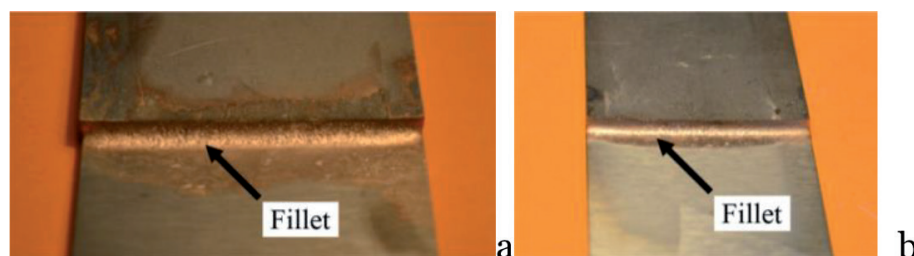
In the central zone (matrix) of the brazed seam, a copper-based solid solution (92.58% Cu) solidifies, which contains a small amount of iron—2.87%, in addition to brazing filler metal component elements (**Figure 3(a)** and **(b)**; **Table 3**).

The more detailed study of chemical inhomogeneity of brazed seam matrix by mapping showed that dispersed particles of 0.5–1 μm size, enriched in iron and silicon, precipitate in the copper-based solid solution (**Figure 4**).

Alloys of the copper-manganese-silicon system contain two phases: a solid solution based on copper and manganese silicides [15]. In the presence of iron in the alloy, silicides are compounds having a hexagonal lattice isomorphic to the lattices Mn<sub>5</sub>Si<sub>3</sub> and Fe<sub>5</sub>Si<sub>3</sub> [17].

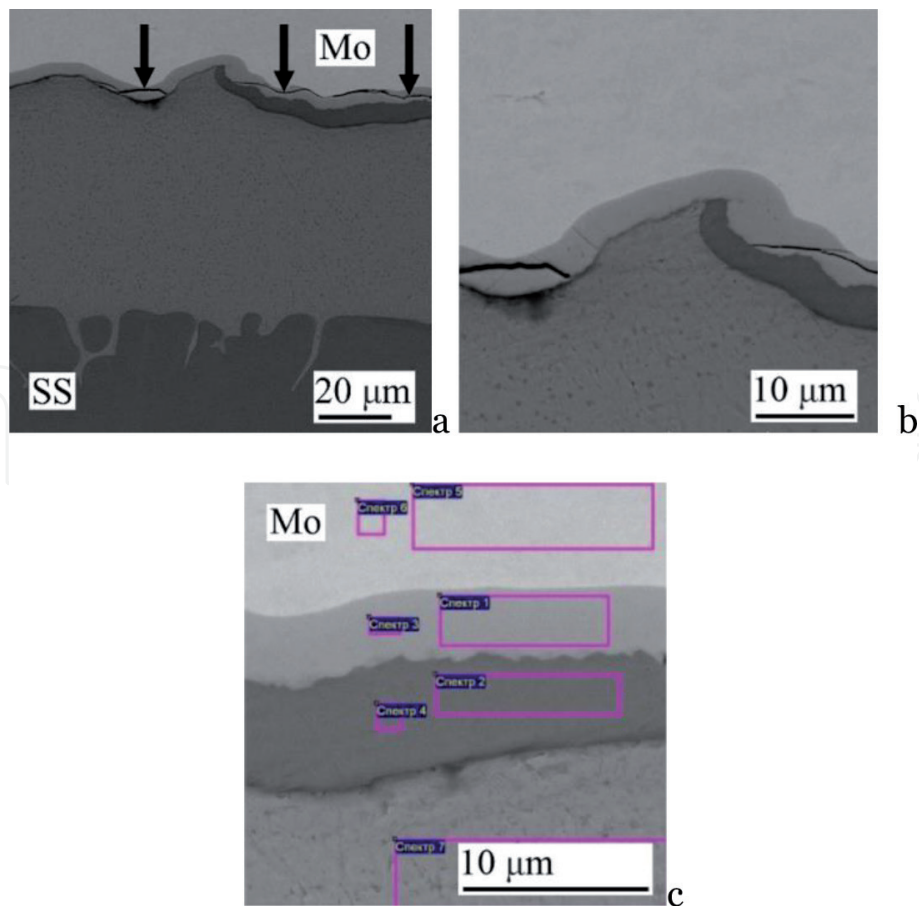
In the peripheral zone of the brazed seam, which borders on molybdenum, two reaction layers are observed, which precipitate in the form of narrow continuous bands along the brazed seam. One of them, based on molybdenum (51.21%), is enriched in iron (31.71%) and silicon (5.88%) and is located closer to molybdenum (**Figure 3(b)**). The second one—based on iron (68.02%)—is also enriched in silicon but contains no molybdenum. It borders on the copper-based solid solution. The width of these reaction layers is variable but does not exceed 5 μm (each). Their common feature is an increased concentration of silicon from 4.83 to 5.88% (**Table 3**). In some areas brazing filler metal penetrates along the grain boundaries of the stainless steel to a maximum depth down to 20 μm (**Figure 3(a)**).

It is evident that during brazing, the liquid brazing filler metal is saturated by steel component elements. Diffusion processes take place at the cooling of



**Figure 2.**

The appearance of the brazed sample of molybdenum-stainless steel, produced using Cu-Mn-Ni-Fe-1Si brazing filler metal: direct (a); reverse (b) fillet.



**Figure 3.** Microstructure (a, b) and studied regions (c) of the brazed joint at the application of Cu-Mn-Ni-Fe-1Si brazing filler metal.

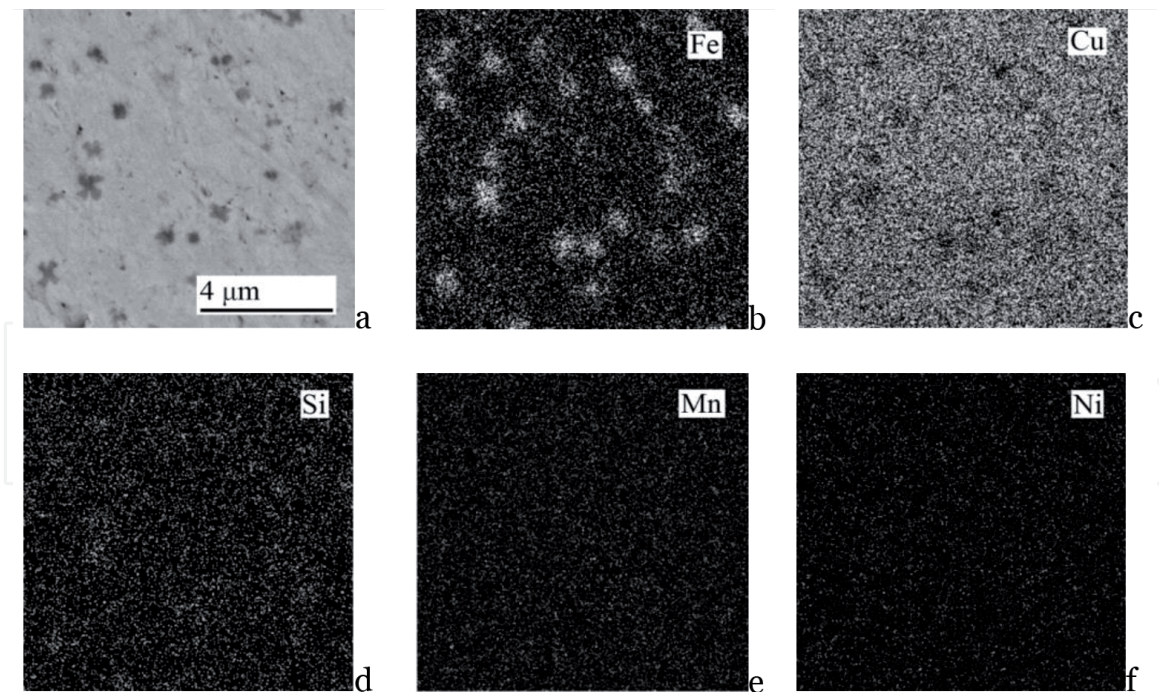
Spectrum No.	Chemical elements, wt. %							
	O	Si	Cr	Mn	Fe	Ni	Cu	Mo
1	—	5.88	7.08	0.77	31.71	2.54	0.81	51.21
2	—	4.83	16.79	2.23	68.02	4.46	3.67	—
3	—	5.65	6.56	0.86	32.07	2.27	0.00	52.59
4	—	4.92	16.50	2.48	66.79	4.63	4.68	—
5	1.74	—	—	—	—	—	—	98.26
6	1.85	—	—	—	—	—	—	98.15
7	—	—	0.30	3.04	2.87	1.21	92.58	—

**Table 3.** Chemical composition of individual phases of brazed joint.

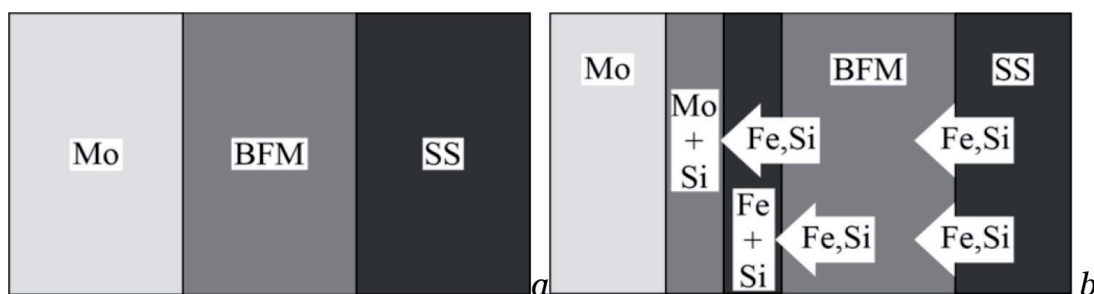
brazed joints under nonequilibrium conditions and in the presence of a gradient of concentrations of chemical elements of base metal and brazing filler metal. Silicon and iron from the stainless steel diffuse into the brazing filler metal (**Figure 5(a)** and (**b**)).

In connection with limited solubility of the latter, two reaction layers form along the molybdenum-brazing filler metal interface (**Figure 5(b)**).

Longitudinal cracks (**Figure 4(a)**) are observed in the molybdenum-based reaction layer (51.21–52.59%), enriched in iron 31.71–32.07% (**Table 3**—Spectrum 1, 3), and on molybdenum-brazing filler metal interface (along the seam).



**Figure 4.**  
 The electronic image of the microstructure of the brazed seam matrix (a) and the qualitative distribution of iron (b), copper (c), silicon (d), manganese (e), and nickel (f).



**Figure 5.**  
 Schematic image of the formation of the brazed joint: before (a) and after brazing (b).

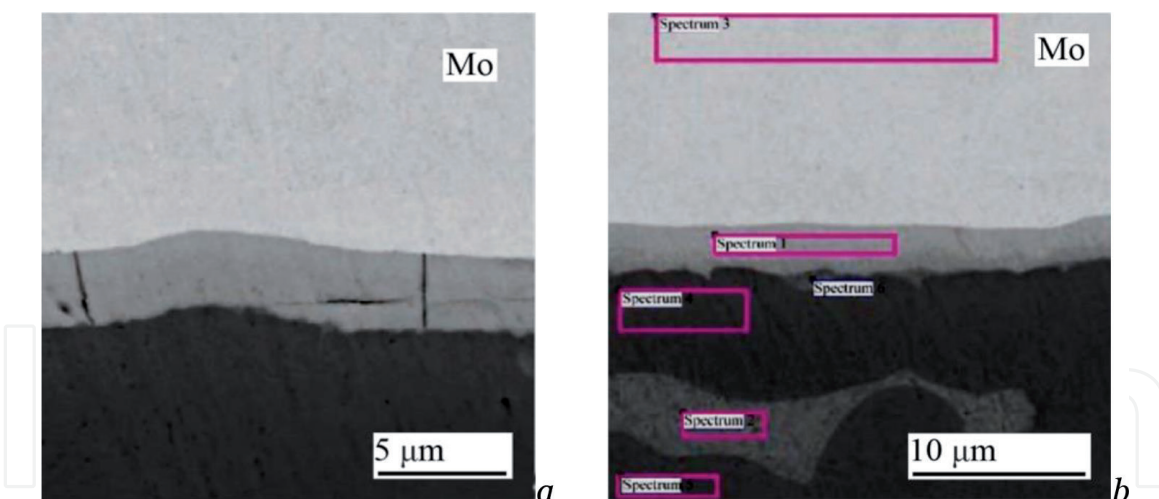
### 3.2 Microstructure of brazed joints of molybdenum with stainless steel at the application of brazing filler metal of Cu-Mn-Ni-0.2Si

Lowering of silicon concentration in brazing filler metal from 1 to 0.2 wt. % does not eliminate the formation of reaction layers on the interface of brazing filler metal—molybdenum (**Figure 6(a)** and **(b)**). At brazing temperature of 1100°C ( $\tau = 5$  min), reaction layers also form along the brazed seam at the interface with molybdenum.

The results of micro X-ray spectral analysis showed that silicon concentration in the reaction layer based on molybdenum (63.41%) does not exceed 0.92% (**Figure 6**), which is significantly lower than in the previous sample (in brazing with Cu-Mn-Ni-Fe-1Si brazing filler metal). The quantity of the other component elements, namely, iron, chromium, nickel, and manganese, is on the same level as in the previous sample (**Table 3**—Spectrum 1). The obtained investigation results show that microcracks form in some regions of the reactive layer (**Figure 6 (a)**). They are located normal to the reaction layer and base metal plates. Cracks are absent in the central zone of the brazed seam, consisting of a solid solution based on copper and dispersed inclusions.

According to binary phase diagrams, consisting of metallic systems, the molybdenum-iron system has considerable regions of solubility at high temperatures.





**Figure 6.**

Microstructure (a) and studied regions, in which chemical composition (b) was determined in the brazed joint of molybdenum-stainless steel (Cu-Mn-Ni-0.2Si brazing filler metal).

However, with temperature lowering, these regions are quickly reduced, and at room temperature, the mutual solubility is practically absent. Some intermetallic phases form between the considered areas [13].

### 3.3 Microstructure of brazed joints of molybdenum with stainless steel at the application of brazing filler metal of Cu-Mn-Ni system

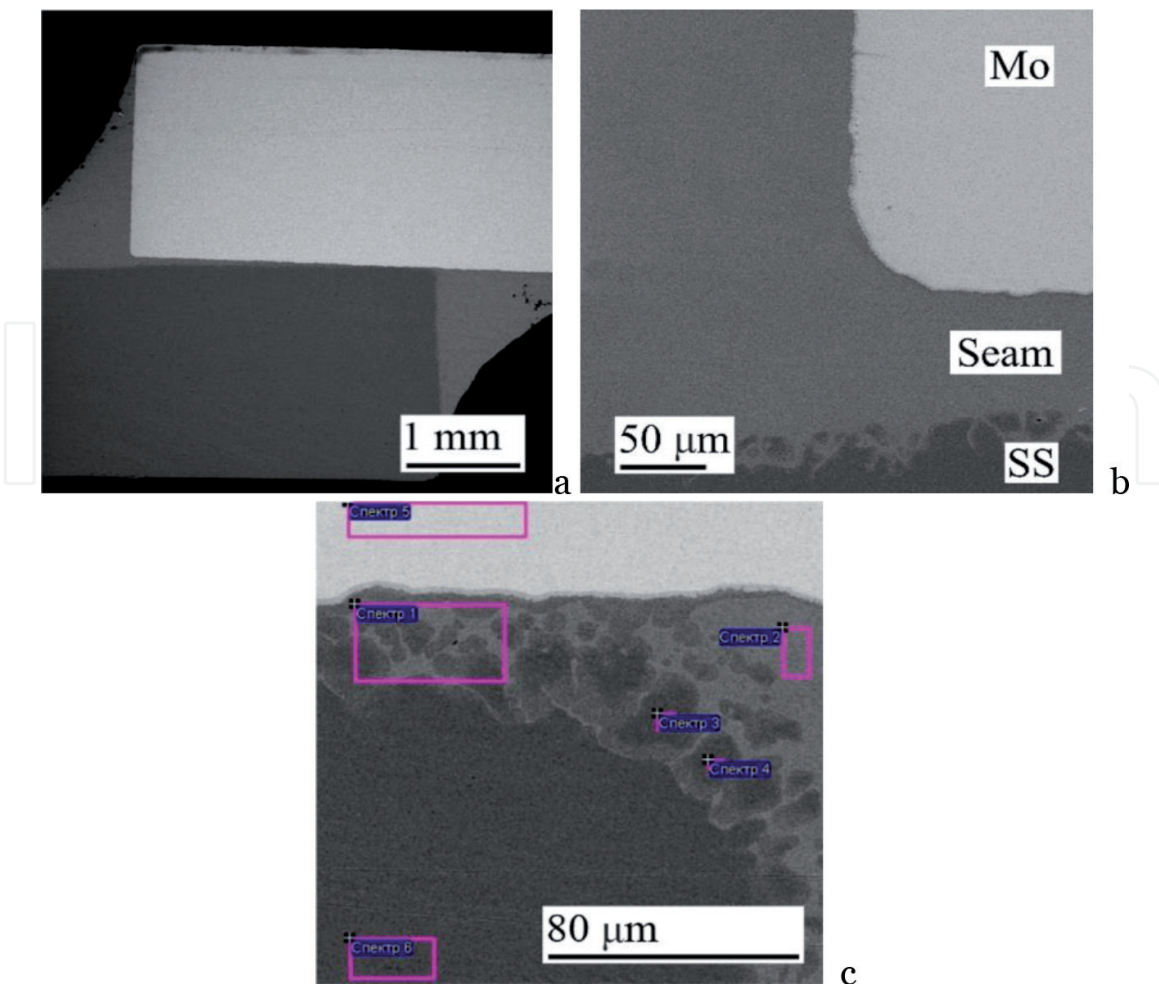
Brazing filler metal of Cu-Mn-Ni system, not containing silicon [18], was used, to prevent cracking in brazed joints. In brazing with this brazing filler metal of dissimilar joints of stainless steel-molybdenum ( $T_b = 1100^\circ\text{C}$ ,  $\tau = 3$  min), the structure of direct fillet differs from that of the reverse one by its morphology and chemical composition (**Figure 7(a)** and **(b)**).

This is due to the features of the sample assembly before brazing. The cast brazing filler metal is placed at the gap on the plane of the plate to be brazed. During brazing, the brazing filler metal melts, and the liquid phase flows into the capillary gap, wets the solid surface being brazed, and is saturated by elements of base metal (steel). Brazed joint forms as a result of thermal and physicochemical interaction of the brazing filler metal and base metal [19]. The interaction of liquid copper brazing filler metal and solid base metal at brazing temperature results in the dispersion of the latter (stainless steel).

Micro X-ray spectral analysis showed that the direct fillet consists of copper matrix-solid solution, containing 4.31 wt. % iron (**Figure 7(a)** and **(b)**). In the copper matrix of reverse fillet, the weight fraction of iron practically does not change (4.19 wt. %), but a considerable number of dispersed particles based on iron (67.83–67.89 wt. %, **Figure 7 (c)**, **Table 4**) appears. They also contain nickel (8.80–9.31%), chromium (17.81%), and a small amount of the other component elements of the brazing filler metal and base metal (**Figure 7 (c)**, **Table 4**).

These results confirm the identity of the chemical composition of stainless steel and dispersed particles located in the solid solution.

From the side of the reverse fillet, brazed seam forms similarly. Round particles of different size based on iron (44.15%) are located in the brazed seam matrix—in the solid solution, and take up a large area of the braze seam [19]. Their composition includes all the elements of brazed metals and brazing filler metal: chromium, nickel, manganese, copper, silicon, and molybdenum (**Figure 8 (a)**, **Table 5**).



**Figure 7.**  
 The appearance of the brazed sample (a), the microstructure of direct fillet regions (b), and studied areas of reverse fillet region (c).

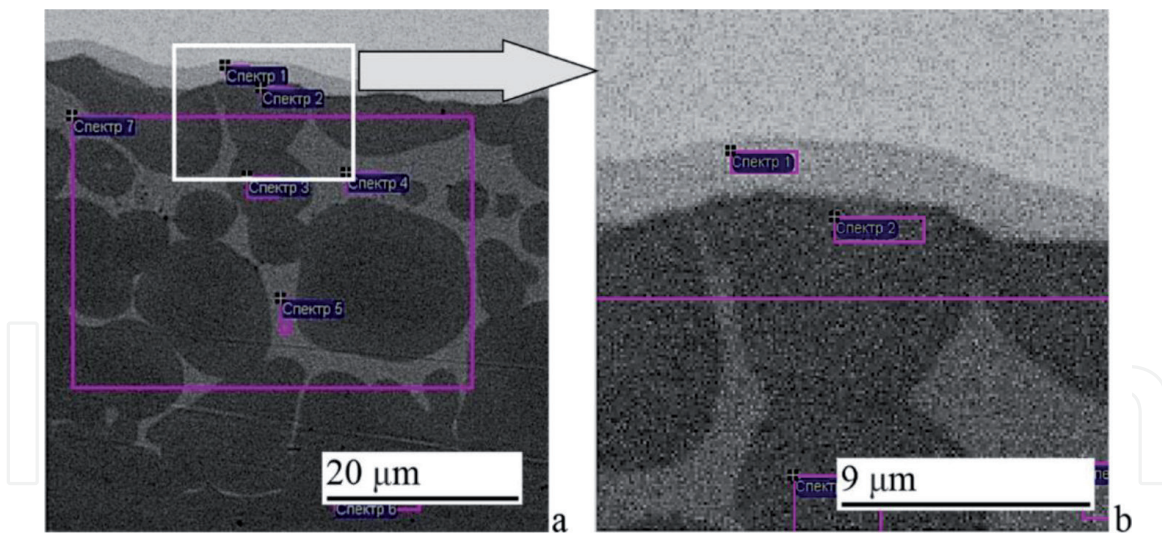
Spectrum No.	Chemical elements wt. %							
	Si	Ti	Cr	Mn	Fe	Ni	Cu	Mo
1	0.22	0.10	5.73	3.30	22.47	11.92	55.00	1.24
2	0.15	0.00	0.84	5.30	4.19	8.59	80.51	0.44
3	0.63	0.46	17.81	1.88	67.83	9.31	1.80	0.27
4	0.67	0.26	17.81	1.93	67.89	8.80	2.25	0.39
5	0.10	0.00	0.00	0.00	0.00	0.00	0.00	99.90
6	0.70	0.39	18.44	1.94	68.69	8.92	0.91	0.00

**Table 4.**  
 Chemical composition of the fillet area.

Such stainless steel elements, as iron and chromium, are found in the copper-based solid solution, but in much smaller amounts of 3.27–3.45 and 0.62–0.64%, respectively.

Two reaction layers in the form of continuous bands (about 2.4 μm width) are also observed along the brazed seam from molybdenum side. One is based on molybdenum and contains an increased concentration (wt. %) of iron, 22.27%; chromium, 7.29%; and silicon, 0.84% (**Figure 8(a)** and **(b)**; **Table 5**). The second one is based on iron.

Obtained data of X-ray spectral analysis show, that similar formation of brazed joints proceeds at the application of brazing filler metals of Cu-Mn-Ni-Fe-1Si and



**Figure 8.**

*The microstructure of brazed seam of Mo-SS joint produced at 1100°C brazing temperature.*

Spectrum No.	Chemical elements, wt. %							
	Si	Ti	Cr	Mn	Fe	Ni	Cu	Mo
1	0.84	0.00	7.29	0.99	22.27	4.11	0.71	63.78
2	0.29	0.09	6.77	3.38	24.82	8.25	48.08	8.32
3	0.46	0.10	11.25	3.55	44.15	16.77	21.57	2.15
4	0.00	0.08	0.64	5.29	3.27	3.79	86.66	0.27
5	0.08	0.00	0.62	5.14	3.45	3.61	86.86	0.24
6	0.84	0.68	18.33	1.95	68.13	8.59	1.14	0.34
7	0.29	0.16	8.34	2.98	30.10	7.84	49.10	1.19

**Table 5.**

*Composition of brazed seam.*

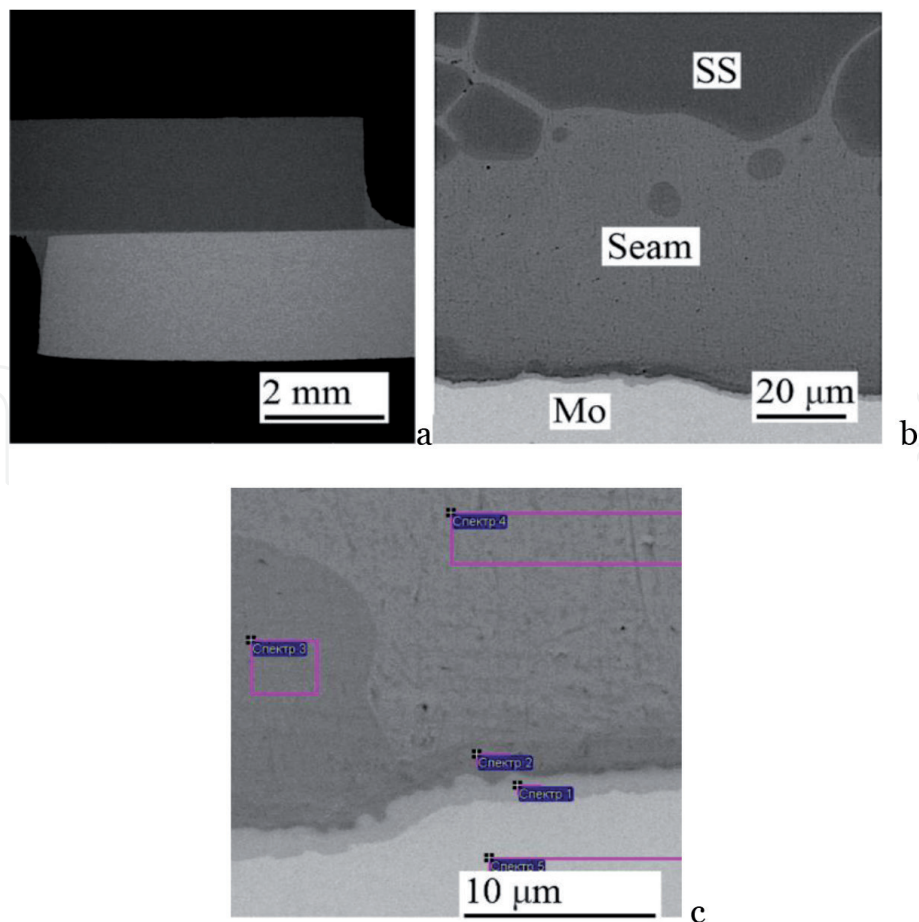
Cu-Mn-Ni systems. In both the variants, reaction layers form on molybdenum-brazing filler metal interface. In the first case (Cu-Mn-Ni-Fe-1Si), silicon and iron are present in the brazing filler metal. In the second variant (Cu-Mn-Ni), these elements diffuse from the base metal into brazed seam metal, leading to its saturation with component elements of stainless steel and formation of reaction layers on the interface. The difference between the chemical compositions of these layers consists in that silicon concentration is significantly lower in the second variant, compared to the first one.

The results of the conducted studies show that lowering of the temperature of brazing the dissimilar joints to 1084°C allows avoiding base metal dispersion and ensures the formation of tight homogeneous brazed seams (**Figure 9(a)** and **(b)**).

In individual areas of the seams, the brazing filler metal penetrates along the boundaries of stainless steel grains to the depth of 15–20 μm.

It should be noted that the reaction layers at the interface of molybdenum-brazing filler metal form in a similar way (**Figure 9(c)**, **Table 6**), as in brazing other samples, described above. However, their width decreases: from 2.4 μm to 1.7 for the molybdenum-based layer and to 1.8 μm—for the iron-based layer.

Results of local micro X-ray spectral analysis show that the maximum concentration of silicon in the layer near molybdenum does not exceed 0.78%. Brazed seam matrix, similar to the previous samples, is represented by copper-based solid solution (**Table 6**—Spectrum 4; **Figure 9(c)**) with inclusions of dispersed particles. It contains



**Figure 9.** The appearance (a), microstructure (b), and studied areas (c) of brazed seam of Mo-SS joint, produced at 1084°C brazing temperature.

the same concentration of component chemical elements, as does the solid solution at brazing temperature of 1100°C [19]. A small area of the microsection field of view (about 1%) is made up by particles (of 2–10 μm size) enriched in iron (35.45–39.54%) and other component elements of stainless steel (Table 6, Figure 9(c)).

In keeping with state diagrams of binary metal systems, iron and copper have limited solubility at elevated temperature, but with temperature lowering their solubility decreases, and at 20°C it is practically absent. The iron-nickel binary system is characterized by the existence of a continuous series of solid solutions between γ-iron and nickel at elevated temperature. Temperature lowering leads to the formation of several intermediate ordered phases (Fe<sub>3</sub>Ni, FeNi, FeNi<sub>3</sub>). Copper-nickel system is characterized by the formation of a continuous series of solid solutions [13, 20]. Thus, it can be assumed that individual particles of intermediate

Spectrum No.	Chemical elements, wt. %						
	Si	Cr	Mn	Fe	Ni	Cu	Mo
1	0.78	7.17	1.09	26.15	9.81	2.65	52.34
2	0.23	7.40	3.72	36.66	28.62	18.86	4.52
3	0.26	7.36	4.00	35.45	29.33	18.18	5.42
4	0.07	1.25	6.17	6.86	12.60	72.67	0.38
5	—	—	—	—	—	—	100.00

**Table 6.** Composition of brazed joint at 1084°C brazing temperature.

phases form against the background of copper-based solid solution at brazed seam solidification. At the same time, it should be noted that at brazing, the brazed seam metal solidification proceeds under nonequilibrium conditions (in the capillary gap) in the presence of a concentration gradient on the interface, leading to saturation of brazed seam metal with the component elements of the brazed metal [21]. Diffusion processes in the brazed seam result in the formation of particles based on the iron-nickel-copper system. In the brazed seam—copper-based solid solution, iron concentration is significantly lower and is equal to 6–7%.

#### 4. Mechanical properties of dissimilar brazed joints of molybdenum-stainless steel

Metallographic and micro X-ray spectral investigations of brazed joints were followed by mechanical shear testing (at room temperature) of overlap flat samples of dissimilar joints of molybdenum-stainless steel (**Figure 10**).

Brazed overlap samples were tested by axial tension. To ensure the conditions of combining the load axis and the plane of the brazed seam to the sections of the samples that are placed in the grips of the testing machine, stainless steel plates were welded. They help to reduce the eccentricity of the sample during mechanical tests.

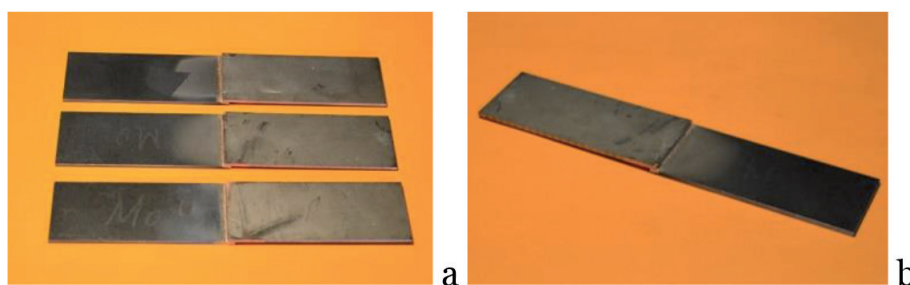
The mechanical properties of brazed joints depend on the microstructure of the brazed joints [6, 16]. The obtained results of mechanical tests of flat overlap samples of dissimilar joints of molybdenum-stainless steel are in good agreement with previous structural studies. Brazing filler metal of the copper-manganese-nickel system containing silicon contributes to the formation of phases enriched in silicon (silicides). They stand out at the interface between the base metal—brazing filler metal [22] and reduce shear strength. The use of brazing filler metal with a solid solution structure without silicon allows obtaining higher values of shear strength.

Performed testing showed that application of brazing filler metal based on Cu-Mn-Ni-Fe-Si system, containing up to 1% silicon, cannot ensure the shear strength above 110 MPa (**Figure 11**).

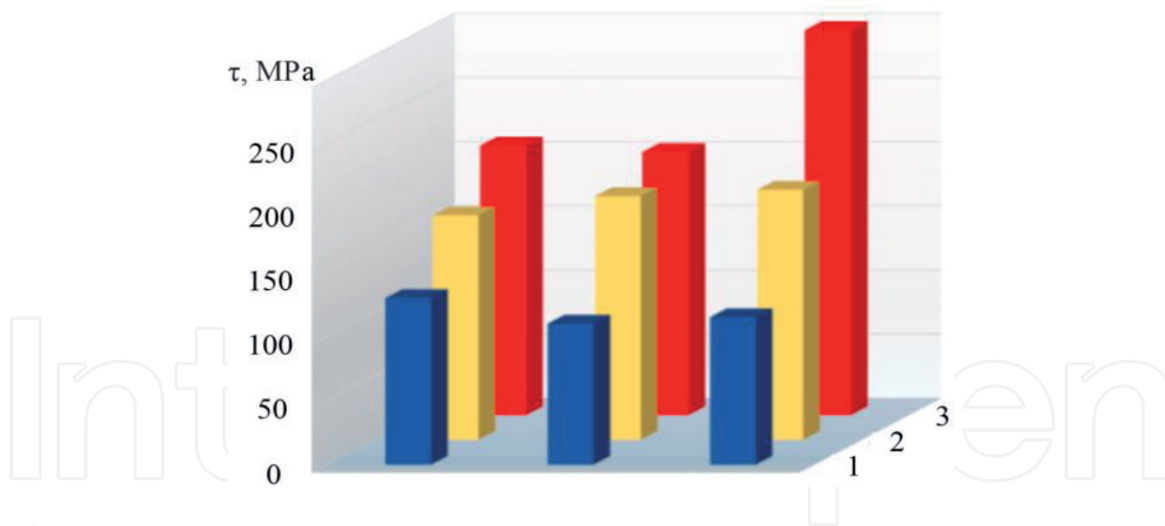
Lowering of silicon concentration to 0.2% in brazing filler metal №2 ensured an increase of shear strength.

At application of brazing filler metals based on Cu-Mn-Ni-Fe-Si and Cu-Mn-Ni-Si systems, samples fail in the brazing seam. Samples produced using brazing filler metal based on Cu-Mn-Ni system fail in the brazing seam, near-seam zone (mixed nature of fracture), and the base metal—molybdenum (**Figure 12**).

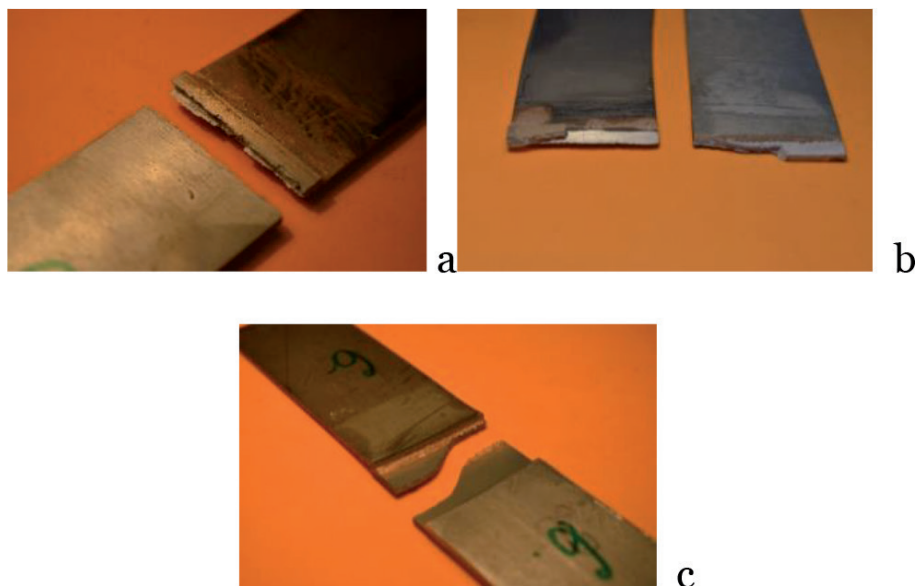
In case of fracture in the seam, the shear strength was on the level of 200–210 (average value of 205 MPa). At fracture through molybdenum, the maximum shear strength was 300 MPa. In some cases, a mixed nature of fracture was observed—partially in the seam and partially in the base metal (**Figure 12(c)**).



**Figure 10.**  
*Appearance of brazed samples of molybdenum-stainless steel.*



**Figure 11.**  
*Shear strength of brazed dissimilar overlap joints of molybdenum-stainless steel.*



**Figure 12.**  
*Brazed samples after mechanical testing: a fracture in the brazed seam (a), near-seam zone (b), and base metal—molybdenum (c).*

When designing telescopic tubular joints from dissimilar materials, molybdenum-stainless steel, it is necessary to take into account the difference in thermal expansion coefficients. The inner tube must be made of molybdenum (with a low coefficient of thermal expansion), and the outer one is made of stainless steel. This design provides a high-quality formation of brazed joints and seams. When brazing some lap joints, the main indicator of quality is tightness (vacuum density), and the strength of the joints is ensured by the large length of the overlap (when using brazing filler metal with a solid solution structure).

The brazed molybdenum-stainless steel telescopic tubular joints with dense seam by high temperature vacuum brazing using system brazing filler metal Cu-Mn-Ni-Fe-Si [23] were manufactured (**Figure 13**).

Checking the brazed telescopic tubular joint Mo-SS for vacuum density gave a positive result. Testing the brazed telescopic tubular dissimilar joints Mo-SS for vacuum density gave a positive result.

In some cases, nonstandard tubular joints of dissimilar metals Mo-stainless steel are used for mechanical testing. In this case, some parameters influence the stability



**Figure 13.**  
The brazed telescopic tubular joint Mo-SS.

of the results obtained: assembly accuracy, the size of the gaps, test equipment, and many others. To improve the quality of brazed lapped tubular joints, a threaded fit is used [24].

## 5. Conclusions

X-ray microspectral studies established that during vacuum brazing of dissimilar joints, molybdenum-stainless steel using brazing filler metal based on the Cu-Mn-Ni-Fe-1Si system in the central zone of the brazed seam forms a copper-based solid solution structure. The mapping showed that dispersed particles of 0.5–1  $\mu\text{m}$  size, enriched in iron and silicon, precipitate in the copper-based solid solution. The peripheral zone of the seam (on the molybdenum side) is formed by reactive layers, based on iron (width 5.3  $\mu\text{m}$ ) and based on molybdenum (width 3.2  $\mu\text{m}$ ), which stand out in the form of continuous strips along the soldered seam. At a silicon concentration in the brazing filler metal (1%), these zones are enriched in the latter, which leads to the formation of silicides at the interface and cracking.

It is shown that when using brazing filler metal based on the Cu-Mn-Ni system ( $T_n = 1100^\circ\text{C}$ ), the base metal is dispersed with the release of particles based on iron in a solid solution based on copper and reactive layer about 2.4  $\mu\text{m}$ .

Lowering of brazing temperature to  $1084^\circ\text{C}$  allows avoiding base metal dispersion. It ensures the formation of brazed seams with the homogeneous solid solution structure based on copper and single dispersed inclusions of the phase enriched in iron. It was found that the width of the reactive layer decreases to 1.7–1.80 microns, but the concentration ratio of chemical elements remains the same as at a temperature of  $1100^\circ\text{C}$ . In some areas, brazing filler metal penetration along the grain boundaries of the base metal of stainless steel is observed.

Mechanical testing of brazed joints of molybdenum-stainless steel proved that brazed joints produced with application of brazing filler metal based on Cu-Mn-Ni system are characterized by maximum values of shear strength. Brazed samples fail both in the seam and in the near-seam zone (strength level of 200–210 MPa) and the base metal (molybdenum) at 300 MPa.

Developed technological process of brazing such dissimilar materials as molybdenum and stainless steel can be applied, when producing individual brazed components of dissimilar materials in the nuclear and aerospace industry and at the development of the fusion reactor.

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