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CHARACTERISTICS OF FORMATION AND PROPERTIES OF BRASS–STEEL JOINT PRODUCED BY AUTOVACUUM CLADDING

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ABSTRACT

The technological features of producing a brass–steel joint by the method of autovacuum heating are considered. The thickness of the brass layer after machining was 10 mm. Studying the structures and chemical composition of various joint zones confirmed the solution-diffusion nature of interaction of liquid brass with steel. Microhardness measurements showed absence of hard and brittle structures. A high quality of the joint was confirmed by mechanical tests of the two-layer joint for static bending, tear and shear.

KEYWORDS: brass, steel, two-layer joint, autovacuum heating

INTRODUCTION

The joints of brass and carbon steels are used in manufacture of various products. These are two-layer sleeves, supporting components [1], rolled sheets with a cladding layer from copper alloys [2], joints of steel and cast iron parts, where brass is used as filler metal [3]. These joints mostly form under atmospheric pressure. Brazed joints are also produced in vacuum or controlled atmosphere.

Normative documents for manufacture of tube plates for modern tubular heat exchangers envisages a high quality of brass–steel joint at joint area of more than $1.5 \cdot 10^4$ cm^2 and 10 mm thickness of the cladding layer [4].

The objective of the work is development of a cost-effective technology of producing a sound brass–steel joint of a large area with up to 10 mm thickness of the brass. Here, equipment currently available at industrial enterprises should be used.

The experimental part of this work is a continuation of the performed studies of liquid copper interaction with steel [5] and it confirmed their main conclusions.

EXPERIMENTAL MATERIALS AND PROCEDURE

The steel base of the joint was made from St14G2 steel [6], the brass layer — from L59 brass [7]. The assembled package for cladding was sealed by making vacuum-tight welds. 2NVR-5DM vacuum pump was used to pump air out of the package to $2 \cdot 10^{-2}$ Pa. Samples were heated in SNOL-04534 thermal furnace.

Metallographic analysis method was used to study the macro- and microstructure of the longitudinal and transverse sections of the produced joints. Investigations were performed using Neohpot-32 optical microscope, fitted with an attachment for digital filming. The system of image recording was realized using QuickPhoto computer program.

Samples for metallographic investigations were prepared by standard procedures. Microhardness was measured in M-400 hardness meter of LECO Company at 0249 and 0496 N. The reagents for revealing the sample microstructure (Table 1) were selected, based on our developments and recommendations of work [8].

Sample investigations by the methods of scanning electron microscopy (SEM), and X-ray microprobe analysis (XRMA) were conducted in Jamp-9500F instrument of Jeol Company, Japan, fitted with X-ray energy-dispersive spectrometer INCA Penta FET×3 (OXFORD INSTRUMENTS). The energy of the primary electron beam was equal to 10 keV at 0.5 mA current for SEM and XRMA methods and 10 mA current for Auger-electron spectroscopy. Auger spectra were recorded with energy resolution $\Delta E/E = 0.6$ %.

Table 1. Reagents for metallographic etching of the samples

Etching purpose	Reagent composition	Method of application	Note
Revealing the microstructure	HNO_3 — 50 ml H_2O — 50 ml	Chemical etching at intensive stirring of the reagent $t = 20$ °C, $\tau = 5$–30 s	Oxide film removal: HCl — 20 ml H_2O — 80 ml, $\tau = 1$–3 s, $t = 20$ °C
Revealing the macrostructure	HNO_3 — 50 ml H_3PO_4 — 25 ml (CH_3COOH) — 25 ml	Chemical etching at intensive stirring and heating of the reagent up to $t = 70$ °C, $\tau = 5$–30 s	

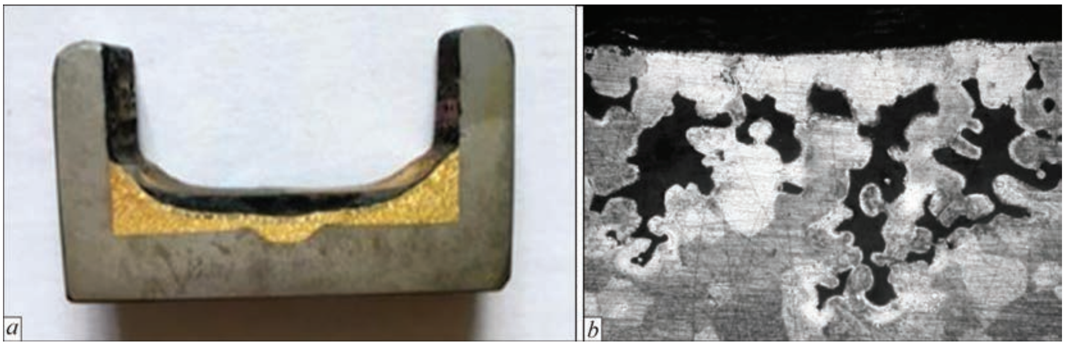

Figure 1. Brass–steel joint produced by open heating: *a* — joint macrosection; ×1.5; *b* — discontinuity in the surface layer of brass, ×100

Prior to investigations, the sample surface was cleaned directly in the instrument analysis chamber by etching by argon ions Ag^+ with 1 keV energy for 10 nm/min. SiO_2 etching rate was nm/min. Vacuum in the analysis chamber was in the range of $5\cdot10^{-8}$–$1\cdot10^{-5}$ Pa.

EXPERIMENTAL RESULTS

Obtaining a sound brass–steel joint by pouring using open heating in a thermal furnace is impossible, because of formation of pores and discontinuities in brass, provoked by zinc evaporation [9]. Here, the brass layer surface has defects to the depth of down to 500 μm. It leads to high labour consumption for machining of the brass surface and additional brass consumption for technological allowance. Figure 1 shows a brass–steel joint, produced by open heating, and the microstructure of the brass surface layer.

When searching for a replacement for open heating, the following known methods of producing two-layer brass–steel billets were considered: explosion welding [10], submerged-arc surfacing [11], laser welding [12], plasma surfacing [13], etc. Application of these technologies, however, requires designing and manufacturing special equipment.

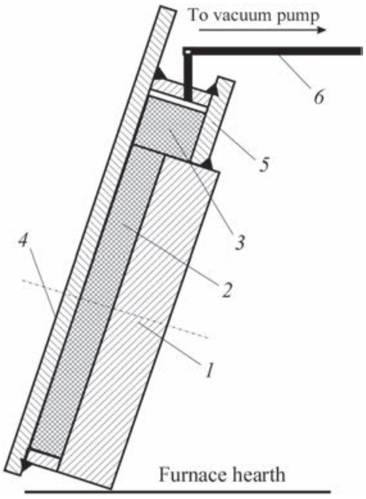

Figure 2. Scheme of cladding the billet by flowing with forced replenishment: *1* — carbon steel base; *2* — brass sheet; *3* — brass for replenishment; *4* — cover; *5* — accumulator; *6* — nozzle for vacuum pump

Current experience of brazing application in autovacuum to produce brass–steel joints [14] showed that this technology ensures a high quality of the joint at 0.5–3.0 mm thickness of the brass layer. Autovacuum application envisages use of available industrial equipment with minor additions. First of all, it was necessary to ensure deposition of a cladding layer of a uniform thickness at minimum allowance for machining, which was achieved by application of a scheme of cladding with forced replenishment (Figure 2).

All the welds were made on the assembled package and checked for tightness. A vacuum pump was used to pump out air from the inner cavity to $2\cdot10^{-2}$ Pa. The assembly was heated in a standard thermal furnace at T = 1000 °C and soaking for 15 min. Cooling was performed with the furnace to 400 °C, then — with open door at atmospheric conditions.

A feature of heating the assembly located in the container with a vacuumized cavity, is the fact that heat transfer is performed only by radiation due to absence of gas in the cavity. The time required for the assembly heating is equal to 13 min, for specific dimensions of the clearance between the container walls and assembly surface. Therefore, when designing the heating mode it was necessary to increase the assembly soaking time at brazing temperature by 13(15) min.

At examination of the brass layer (after removal of the cover by machining) it was found that brass melted completely both in the main cavity, and in the replenishment cavity, and good wetting of the steel part is in place. No pores or discontinuities were observed in the brass cross-section (Figure 3).

The strength and reliability of brass–steel joint is directly related to the structure and composition of metal in the contact zone. Metallographic investigations showed that St14G2 steel preserves its ferrite-pearlite structure after heating. The structure of L59 brass is two-phase (α+β), it consists of a light-coloured α-matrix and small areas of β-phase, which etches darker (Figure 4). After performance of analysis, it was found that chemical composition of brass changed after heating, and zinc content dropped from 40 to 37 wt.%.

Table 2. Chemical composition of meal of the studied joint areas, wt.%

Area number	Si	Mn	Fe	Cu	Zn
1	0.10	0.12	18.39	49.66	28.97
2	0.04	0.16	42.72	33.84	20.30
3	0.36	0.16	79.14	10.85	6.95
4	0.22	0.08	76.80	5.68	3.17
5	0.03	0.08	4.34	59.26	33.48
6	0.25	0.00	90.84	3.49	3.09

The questions of liquid brass interaction with solid steel are fundamental at prediction of the joint reliability. These processes were repeatedly studied by different authors. Some of them state that cracks form on the steel surface at its contact with liquid copper and its alloys during deposition, which are filled with liquid [15]. In this case, the composition of the metal filling the “crack” should be close to the initial one, and the “crack” tip cannot be filled completely, in keeping with the law of capillarity [5].

Another approach to interaction of the melt of copper and its alloys with steel is given in detail in [5]. According to it, the interaction of brass melt with solid steel takes place due to dissolution and diffusion of elements, located on the steel grain boundaries, and further separation and movement of these grains into the melt. In the areas of brass penetration, iron and other components of steel should be registered, in addition to initial elements.

At a considerable magnification, brass penetration into steel was recorded in the optical (Figure 5, *a*) and electron (Figure 5, *b*) microscopes to the depth of 1.5–10 μm. The chemical composition of metal in the studied areas is given in Table 2.

After brass penetration into steel to the depth of 10 μm, a considerable amount of iron is registered in it: 18.39–42.72 wt.% (areas 1, 2). In steel grains that separate and go into brass (areas 3, 4), copper is found in the amount of 5.68–10.85 and zinc in the amount of 3.17–6.95 wt.%. In areas 5 and 6, where no interpenetration of metals is observed, the diffusion processes are less significant. In brass 4.34 % of iron, and in steel 3.49 of copper and 3.09 wt.% of zinc were registered.

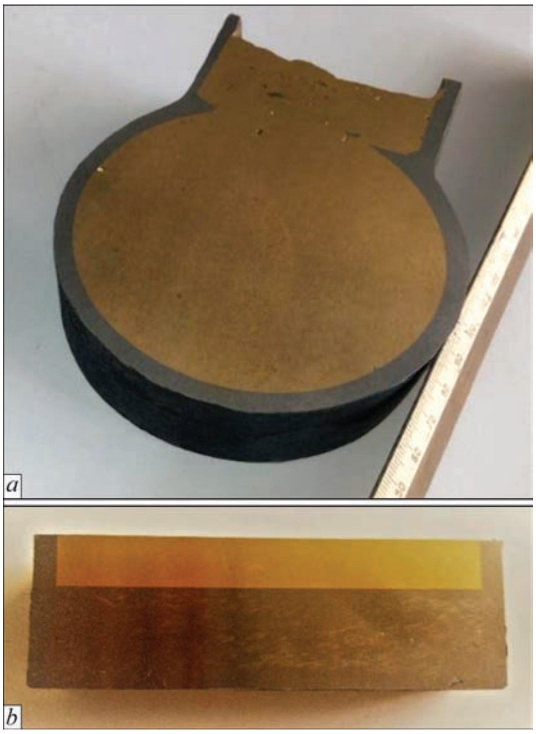

Figure 3. General view (*a*) and diametral cross-section (*b*) of the brass–steel joint produced in autovacuum, ×0.5

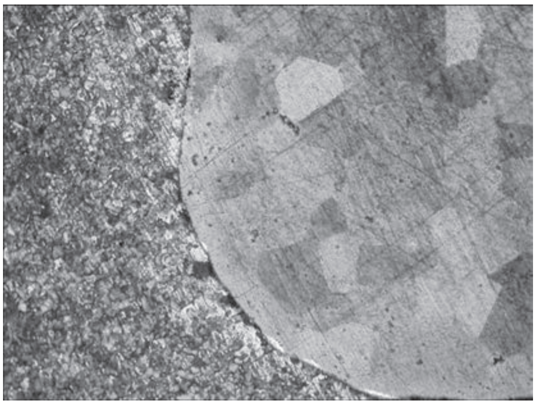

Figure 4. Microstructure of brass–steel joint after etching, ×100

At analysis of microhardness in brass and steel areas located near the contact zone, no formation of solid or

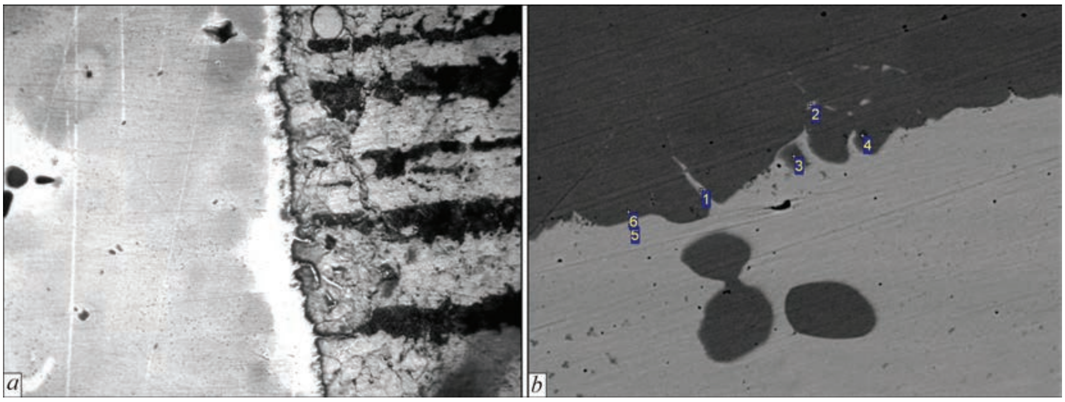

Figure 5. Zone of brass–steel contact: *a* — optical, ×500; *b* — electron microscopic image ×1500 (etched)

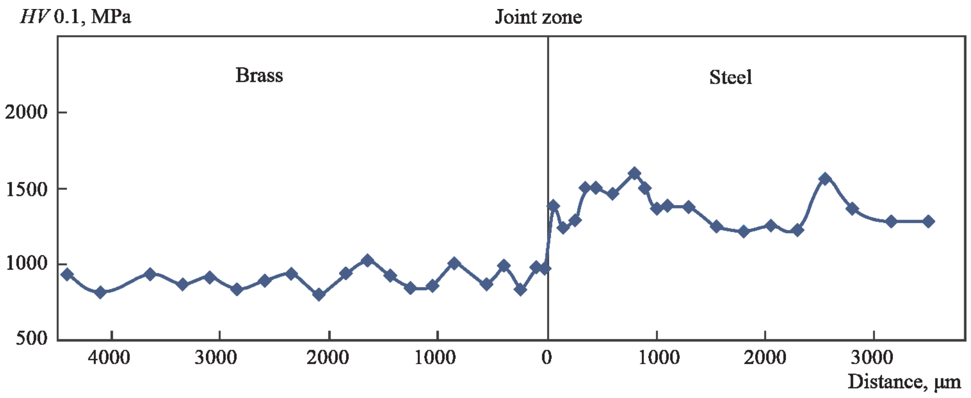

Figure 6. Metal microhardness in brass–steel joint

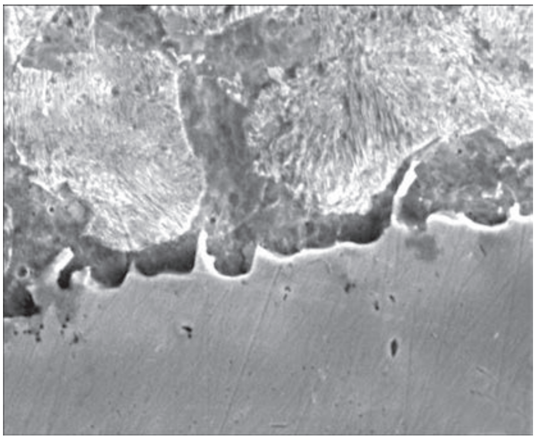

Figure 7. Steel microstructure in brass–steel contact zone, ×1600

brittle structures was found (Figure 6). At the same time, it is necessary to pay attention to the structure of steel in the zone of contact with brass (Figure 7).

The chain of dark grains from the steel side is pearlite grains. Carbon in steel is known not to interact with copper. Its concentration in the contact zone grows which at long-time soaking (more than 30 min) may lead to formation of a chain of brittle grains of pearlite along the contact boundary from the steel side. In this connection, the duration of soaking in the furnace is limited to 15 min. As a result, pearlite accumulations were insignificant which is indicated by microhardness investigations. The same effect was in place, when studying the interaction of liquid copper with steel [5].

Testing for shear of the cladding layer, tearing of the cladding layer and static bending was conducted in order to determine the mechanical characteristics of brass–steel joints. Shear testing of the cladding layer was performed on samples (Figure 8, *a*) which are used for two-layer steels produced by rolling [2]. The thickness of the sample cladding layer was brought to 5 mm by machining. As a result of testing, it was found that the ultimate shear strength of the brass–steel joint produced by heating in autovacuum is equal to 194.2 MPa.

Static tearing tests of the cladding layer were conducted on samples presented in Figure 8, *c*. Here, the die was of such a shape that it ensured tearing deformation in the metal joint zone. The tearing strength limit of the cladding layer was equal to 266.7 MPa.

Static bend testing with cladding layer inside was performed on samples (Figure 8, *b*) of 120×20×8 mm size, die diameter was 16 mm [17]. At 180° bending angle, no cracks visible to the naked eye were found on the sample surfaces.

DISCUSSION OF INVESTIGATION RESULTS

Analysis of the cost of production of a conventional unit of products by arc surfacing, explosion welding and developed technology of heating in autovacuum showed significant cost advantages of the latter. A scheme of the packet positioning at an angle to the vertical with feeding of an additional amount of liquid brass to the cladding layer ensured both obtaining a joint without casting defects or pores, and a high quality of the brass layer surface directly after cladding. Here, the allowance for machining was minimal, metal and labour consumption for machining were also much lower than in other variants.

Metallographic investigations showed that no brittle structures form in the joint zone. The interaction of

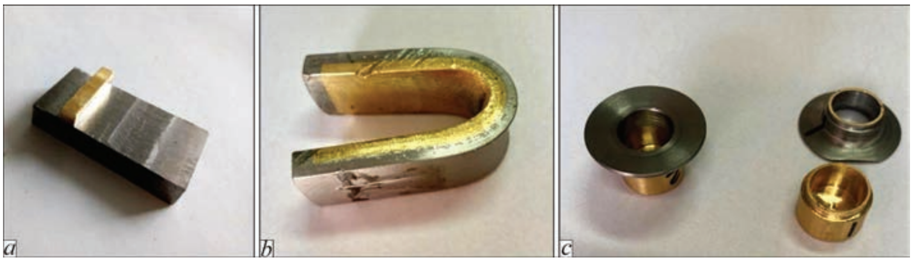

Figure 8. Samples for mechanical testing of brass–steel joints: *a* — shear testing of cladding layer; *b* — two-layer joint after static bend testing with cladding layer inside; *c* — before and after cladding layer tearing tests

liquid brass with steel takes place without cracking in the steel layer. No unfilled tips, or brass penetration into the steel was found, metal composition is close to the initial brass composition with additions of some elements present in the steel. These results correlate well with those of earlier performed studies of liquid copper interaction with steel [5]. No structures with a high hardness form at interaction of steel and brass. The zone of higher hardness of the steel is equal to 3–10 μm. It allows predicting high mechanical properties of the joint and high reliability of the product at operation under the conditions of thermal cycles.

The ultimate shear strength of the brass–steel joint produced by heating in autovacuum was equal to 194.2 MPa, that is by 32 % higher than the normative value (147.1 MPa) [2]. Static bend testing of a two-layer joint with cladding layer inside showed that the joints of metal of the cladding and base layers meet the requirements [6, 2, 16] (out-of-plane bending until sides are parallel, cracks are absent). Tearing strength which was equal to 266.7 MPa, is higher than the normative value by 52 % [10] (177.8 MPa after explosion welding and heat treatment).

CONCLUSIONS

1. A package of engineering works was performed on optimization of the technology of producing a two-layer brass–steel joint by heating in autovacuum. Obtained output data allow developing a production technology with maximal application of the available equipment.

2. Metallographic investigations revealed the high quality of the joint microstructure.

3. Mechanical characteristics of the produced brass–steel joint completely meet the requirements of normative documents for manufacture of tube sheets of shell-and-tube heat exchangers.

4. The performed work is a continuation of investigations of interaction of liquid copper and its alloys with steel at heating in autovacuum. The mechanisms of interaction of the liquid and solid phases published earlier, are completely confirmed in this work.

REFERENCES

1. Kolesov, S.N., Kolesov, I.S. (2007) *Materials science and technology of structural materials*. In: Manual for inst. for higher educ., 2nd Ed., Moscow, Vysshaya Shkola [in Russian].
2. Golovanenko, S.A., Meandrov, L.V. (1966) *Production of bimetals*. Moscow, Metallurgiya [in Russian].
3. (2003) *Handbook on soldering*. Ed. by I.E. Petrunin, 3rd Ed., Moscow, Mashinostroenie [in Russian].
4. GOST 31842–2012. *Shell-and-tube heat exchangers. Technical requirements* [in Russian].
5. Serebryanik, I.P. (2011) *Autovacuum noncapillary structural brazing*. Kyiv, Alfa-Reclama [in Russian].
6. GOST 19281–89. *Rolled steel with increased strength. General specifications* [in Russian].
7. GOST 15527–2004. *Pressure treated copper zinc alloys (brasses). Grades* [in Russian].
8. Bogomolova, N.A. (1978) *Practical metallography*. Moscow, Vysshaya Shkola [in Russian].
9. Perevezentsev, B.N., Krasnopevtsev, A.Yu., Fedorov, A.L. (1991) Study of zinc evaporation in brazing by copper-zinc braze alloys. In: *Abstr. of Pap. of All-Union Sci.-Tech. Conf. on Brazing in Mechanical Engineering, Tolyatti* [in Russian].
10. OST 5.9311–78. *Explosion welding of metals. Bimetallic billets for tube plates of heat exchange apparatuses. General specifications* [in Russian].
11. (1971) *Welding of steel structures*. In: Production of large structures, Issue 20. Ed. by A.I. Volkonsky. Trudy NPI TyaZhMash, Uralmashzavod [in Russian].
12. Shmidt, M., Kuryntsev, S.V. (2014) Producing of bimetal joints by laser welding with full penetration. *The Paton Welding J.*, **4**, 45–48.
13. Suvorin, A.V. (2011) *Electrotechnological installations*. Krasnoyarsk, SFU [in Russian].
14. Poleshchuk, M.A., Atroshenko, M.G., Puzrin, A.L., Shevtsov, V.L. (2014) Estimation of possibility for producing full-strength joint of large steel parts using the method of autovacuum brazing of threaded profile. *The Paton Welding J.*, **10**, 35–37.
15. Vajnerman, A.E. (1981) Mechanism of intercrystalline penetration in surfacing of copper alloys on steel. Avtomatich. Svarka, **6**, 22–29 [in Russian].
16. Serebryanik, I.P., Atroshenko, M.G., Poleshchuk, M.A. et al. (2018) Properties of steel-copper bimetal produced by brazing in autonomous vacuum. *The Paton Welding J.*, **5**, 12–16. DOI: http://dx.doi.org/10.15407/tpwj2018.05.03
17. GOST 14019–2003. *Metallic materials. Method of bending tests*.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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