DOI: http://dx.doi.org/10.15407/tpwj2018.05.03

PROPERTIES OF STEEL-COPPER BIMETAL PRODUCED BY BRAZING IN AUTONOMOUS VACUUM

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It is determined that brazing of copper on steel under conditions of autonomous vacuum in a contact zone promotes formation of an area of increased microhardness, which is eliminated by standard for steel heat treatment. It is shown that content of carbon in steel does not have significant effect on properties of a copper–steel transition zone. It is stated that interaction of liquid copper with steel does not result in formation of cracks in the joining zone under conditions of brazing in autonomous vacuum. It is determined that increase of time of contact of liquid copper with steel results in formation of brittle structures that decreases joint impact toughness. Failure of steel-copper joint takes place along copper in static tensile tests. At that strength properties of brazed layer exceed reference data for strained and annealed copper. 7 Ref., 2 Tables, 9 Figures.

Keywords: *brazing of copper on steel in autonomous vacuum, steel-copper bimetal, structure and properties of transition zone*

Steel-copper parts, combining strength of steel layer and high heat and electric conductivity of copper, find wide application in metallurgy, shipbuilding, mechanical enginnering and other branches of industry. These are, for example, the big friction bearings of ore-pulverizing mills, hearth-level electrodes of direct current arc furnaces, elements of metallurgical furnace molds. In many commercial machines supply of electric current in thousand and more amperes is carried out by bimetal steel-copper buses which combine structural strength of steel and high electric conductivity of copper.

Depending on designation the bimetal parts are produced in a wide range of thicknesses of cladding as well as base layer. In this connection different methods of copper to steel joining are used, namely explosion welding, diffusion welding, electroslag surfacing, arc and induction surfacing, filling and joint rolling.

A method of manufacture of the bimetal parts of such type by means of brazing of copper on steel under autonomous vacuum conditions was developed in recent time. It differs by high quality of joining and does not require application of special equipment [1].

Taking into account that the steel-copper parts are used, as a rule, in the aggregates with high energy consumption at increased temperatures under conditions of continuous thermal cycling, composition and properties of a copper–steel transition zone can be determining for working capacity of part and assembly in whole.

Different methods of arc surfacing of copper on steel can provoke appearance of microcracks in the joint zone, which are caused by high temperature of electric and plasma arc column as well as joint solidification of copper–steel liquid phase [2–5].

Brazing of copper on steel under conditions of autonomous vacuum is carried out in relatively low temperature not exceeding 1150 °C and it is only copper in liquid phase during formation of joint. This allows receiving high-quality bimetal joint [1].

Bimetal parts as a strengthening layer often use structural steels, which are close to each other on content of main components and significantly differ only by carbon content. Therefore, evaluation of effect of carbon content in steels on structure and properties of copper–steel transition zone was performed for rational designing of technological process of copper on steel brazing. Electrical steel, steel 20 and steel 45 [6] with carbon content 0.03, 0.19 and 0.42 %, respectively, were selected for the experiments.

Investigations were carried out on the samples presented in Figure 1.

Steel bodies of 42 mm diameter, produced from corresponding steel, include a groove of 4 mm, in which a copper disk of 3 mm thickness was inserted. The samples were located in a sealed container, which after vacuumization was heated in furnace to 1150 °C temperature with 30 min isothermal holding. The microsections were made from the halves of the samples after brazing and cooling for performance of metallographic examinations of steel–copper transition zone. Figure 2 presents microstructures of the transition zones received in brazing of copper on electrical steel (Figure 2, *a*), steel 20 (Figure 2, *b*) and steel 45 (Figure 2, *c*).

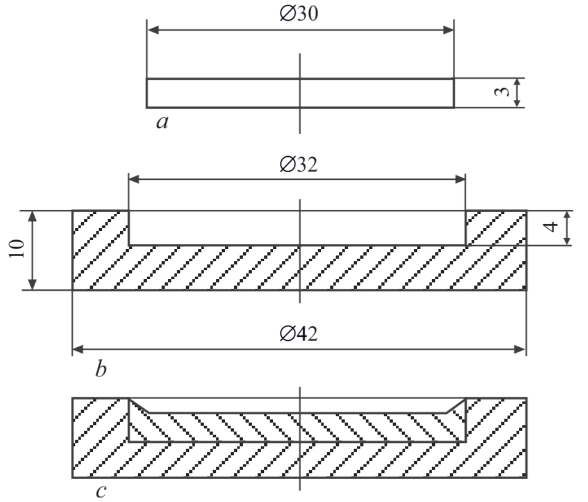

Figure 1. Sample for investigation of interaction of copper melt with steel: *a* — disk from copper; *b* — steel body; *c* — sample section after copper solidification

As it is seen, steel inclusions are observed in all cases in copper at the fusion zone. Increase of carbon content in steel provokes decrease of the amount of such inclusions and, thus, there is reduction of copper penetration along the base metal grain boundaries. Copper melt penetrating in steel along the grain boundaries wraps and tears them (Figure 3).

Further dissolution continues in copper melt. Dendrite base of steel crystallite has, probably, the smallest solubility in the liquid copper, therefore, dendrites after solidification are located in the copper layer (Figure 4).

Figure 4. Steel dendrites in copper layer: *1* — copper; *2* — steel; *3* — steel dendrites

At steel–copper boundary the process of copper penetration and tear of the steel grains with time is again repeated and the fusion zone is displaced to steel side.

There is an opinion that steel cracks under effect of copper melt, which fills the cracks [2–5]. If such a process takes place then there should be on acute-angled area in the crack tip, which will be so narrow that

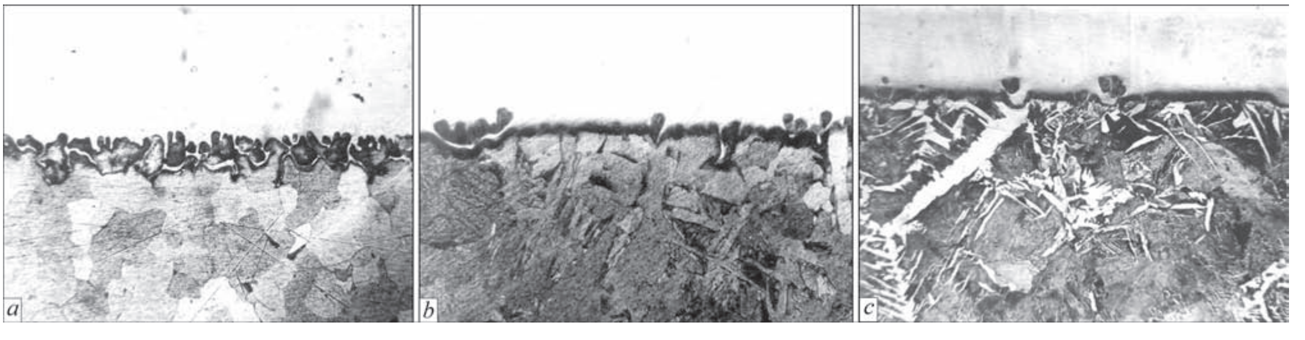

Figure 2. Microstructure (×115) of metal of copper–steel joining zone: *a* — electrical steel; *b* — steel 20; *c* — steel 45

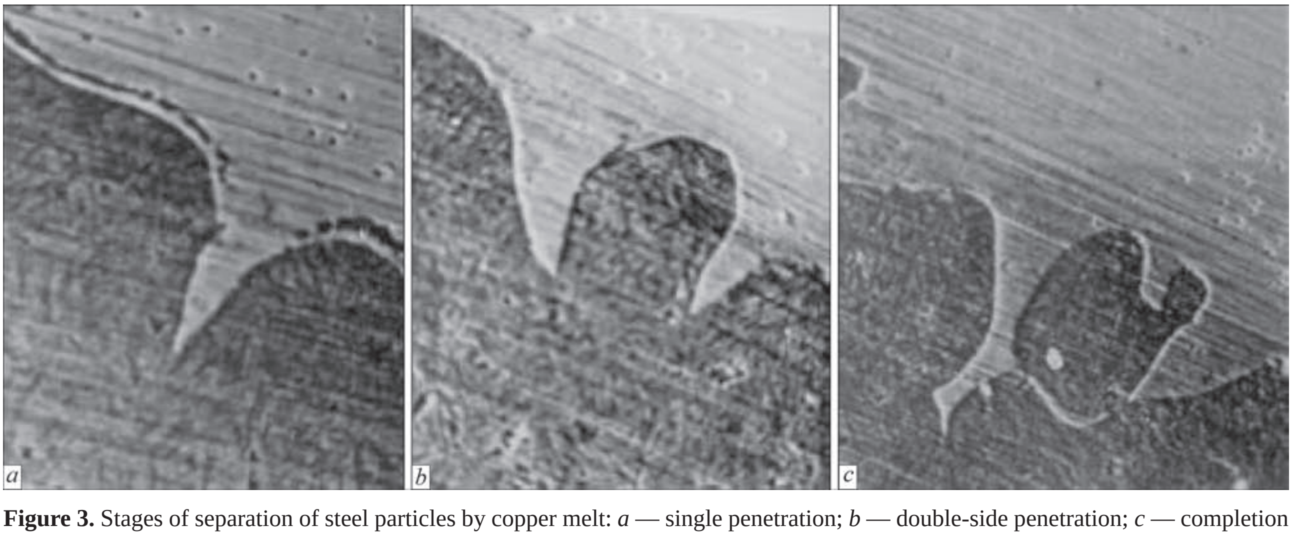

Figure 3. Stages of separation of steel particles by copper melt: *a* — single penetration; *b* — double-side penetration; *c* — completion of steel particle tear

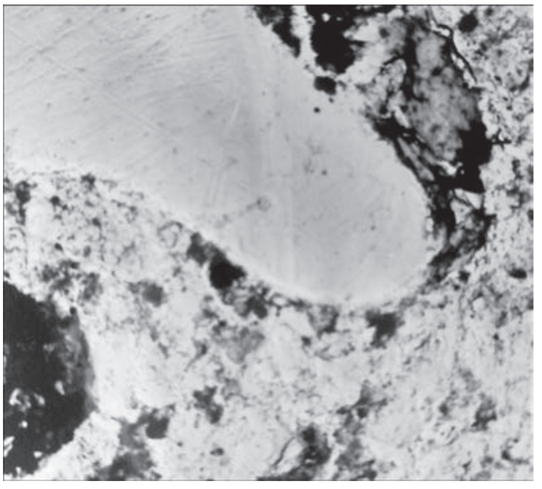

Figure 5. Microstructure (×3000) of joining zone at brazing in autonomous vacuum of copper M1 on steel 20 (T = 1150 °C, isothermal holding 30 min)

due to capillarity conditions liquid copper can not fill it and it will remain empty. Presence of such cracks significantly reduces working capacity of the joint at alternating loads. In order to verify this assumption (type of copper tip penetrated into steel) the samples, received by brazing under autonomous vacuum conditions, were examined using electron microscope at ×3000 magnification (Figure 5).

Tips of copper, penetrated into steel, have smooth curved configuration. There are no cavities. Thus, the hypothesis on steel cracking at contact with liquid copper was not proved by our experiments.

Measurements of microhardness of the steel-copper transition zone were carried out on PMT-3 device. Table 1 gives measurement results. There is a zone of increased microhardness close to the fusion line from steel side. Its extension for electrical steel makes around 80 μm, for steel 20 it is 50 μm and for steel 45 around 25 μm. Such a zone in process of operation can cause appearance of additional stresses and reduce working capacity of the joint.

In order to eliminate this phenomenon the samples were subjected to heat treatment by standard normalizing mode for corresponding grade of structural steel.

Examination of microsections after heat treatment showed that microhardness of the transition zone was significantly reduced (see Table 1).

As was mentioned above, the fusion zone as a result of interaction of liquid copper with steel displaces into steel side.

Virtual depth of groove using indicator depth gage was registered for evaluation of value of this displacement in sample manufacture (see Figure 1). After brazing a point was made at 3.5 mm distance from sample upper edge on polished edge of the sample halves with the help of PMT-3 device. Distance from the reference point to visible fusion boundary was determined in the process of microhardness measurement. As a result of measurements it was determined that the displacement of the fusion line made 220–240 μm for electrical steel, 165–251 μm for steel 20 and 150–180 μm for steel 45. Such a difference in displacement values of the fusion line for steels with different content of carbon at interaction of liquid copper with steel during 30 min shall be declared as insignificant and can be neglected in development of technological processes of copper to steel brazing.

Table 1. Microhardness of metal of transition zone of joint received by autonomous brazing before and after heat treatment

Joint compostion	Distance from fusion line, μm							
	Copper							
	600		50		30		20	
	Without h/t	After h/t	Without h/t	After h/t	Without h/t	After h/t	Without h/t	After h/t
Electr. steel + M1	92	79	93	78	97	66	95	76
Steel 20 + M1	113	87	113	89	115	78	105	92
Steel 45 + M1	93	81	108	81	107	68	116	79

Table 1 (cont.)

Joint compostion	Distance from fusion line, μm											
	Steel											
	10		20		30		50		100		1000	
	Without h/t	After h/t	Without h/t	After h/t	Without h/t	After h/t	Without h/t	After h/t	Without h/t	After h/t	Without h/t	After h/t
Electr. steel + M1	255	116	252	141	237	122	233	114	164	132	153	136
Steel 20 + M1	270	129	250	143	247	124	230	148	191	135	190	143
Steel 45 + M1	269	177	261	176	205	170	200	183	213	188	212	182

Note. Statistically-valid average (from 12–21 measurements) values of microhardness are given.

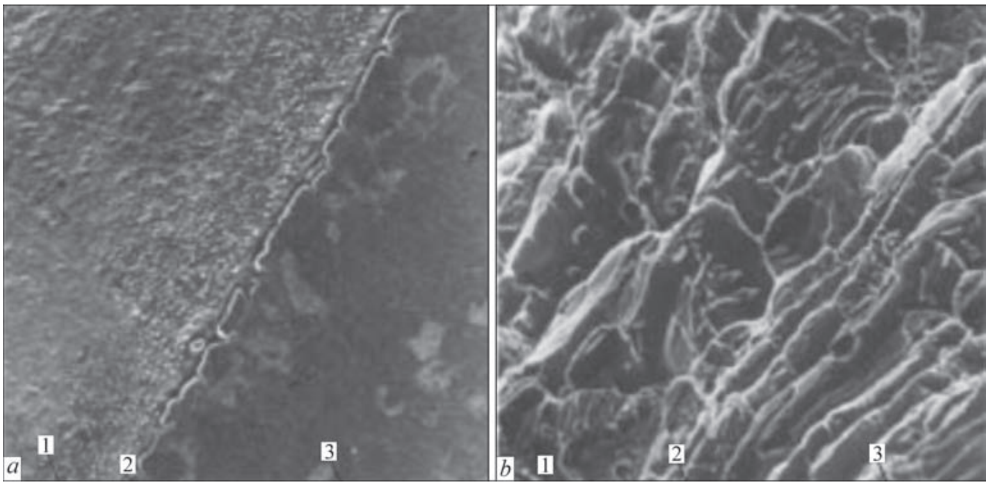

Figure 6. Transition zone of steel-copper joint produced by autonomous vacuum brazing at T = 1150 °C and 30 min isothermal holding: *a* — microstructure (×130); *b* — fracture fractogram (×3000); *1* — copper; *2* — fusion zone; *3* — steel

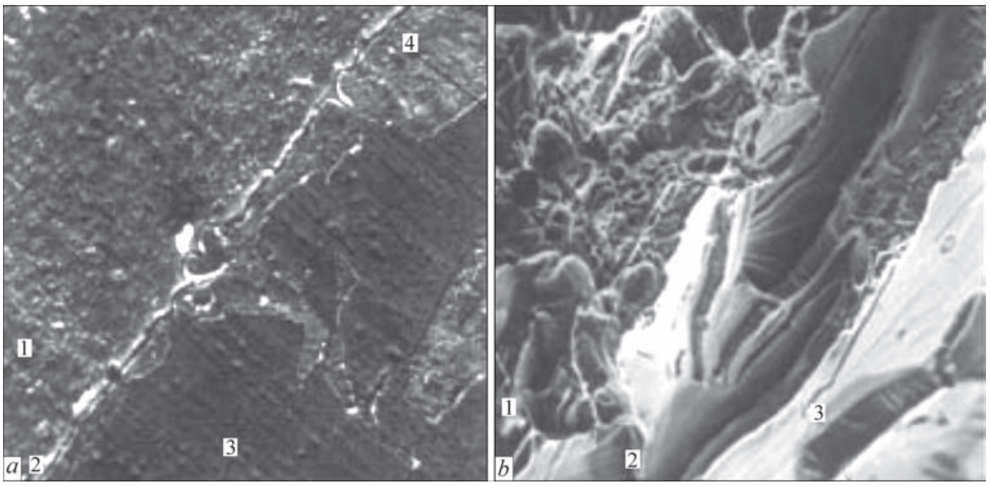

Figure 7. Transition zone of steel-copper joint produced by autonomous vacuum brazing at T = 1150 °C and 2 h isothermal holding: *a* — microstructure (×130); *b* — fracture fractogram (×3000); *1* — copper; *2* — fusion zone; *3* — steel; *4* — chain of pearlite grains in steel

Two samples of steel 20 of 150×100×50 mm size were made in order to determine the optimum time of contact of liquid copper with steel by autonomous vacuum brazing. At that the time of contact of liquid copper with steel at 1150 °C temperature for one sample made 0.5 and for another 2.0 h. After brazing heat treatment, i.e. normalizing on standard for steel 20 mode, was used. The sharp-notch samples for impact bending tests [7] were received from obtained joints in such a way that a failure plane was located across the joint zone. The samples were of 10×10×55 mm size, steel thickness 6 mm; copper thickness 4 mm; depth of a notch passing through both layers was 2 mm.

Figure 8. Template of steel–copper plate (thickness of copper layer 40 mm)

An average value of impact toughness based on the results of tests of three samples made 15.7 mJ/m^2 for holding time 0.5 h and 13.2 mJ/m^2 for 2.0 h. The sample halves after testing were used for production of sections for fractographic and metallographic examinations. There are fine-dispersed inclusions in the copper layer on microsections of the samples with smaller holding time. Steel consists of a ferrite massif, in which small size grains of pearlite are uniformly

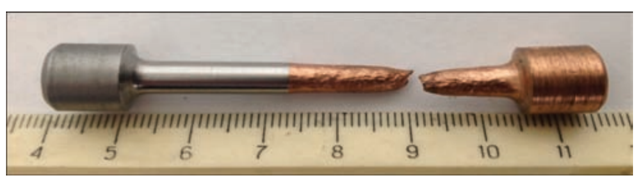

Figure 9. Sample after static tension test

Table 2. Mechanical properties of steel-copper samples

Object and method of investigation	Mechanical properties		
	σ_y, MPa	σ_t, MPa	ψ, %
Static tension test of steel–copper samples (fusion zone)	112.6–127.2 118.1*	281.2–282.9 282.4*	71.1–73.8 72.1*
Strained and annealed copper (standard values)	74	216	75

*Average value based on the results of testing of six samples.

located. Failure of copper and steel has tough nature (Figure 6) on the fractures of samples of this series.

The steps of chip are parallel to each other. This indicates that the failure front was uniformly propagated. In the samples with large holding time copper is saturated with fine-dispersed as well as coarse inclusions (Figure 7).

From the steel side along the fusion line there is a continuous chain of coarse pearlite grains. Copper failure has tough nature. At the same time steel failure is brittle and intragranular. Direction of flows indicates that the failure takes place from structural constituents located on the fusion line. With sufficient assurance its can be assumed that pearlite grains were the source of failure. Such nature of failure can have negative effect on joint working capacity and, thus, the time of contact of liquid copper with steel shall be reduced, if possible.

Based on carried investigations the optimum parameters of technological process were selected and autonomous vacuum brazing of plate from steel 20 of 400×500×50 mm size by copper M1 was carried out. The thickness of copper layer made 40 mm (Figure 8).

The samples of 40 mm for static tension tests were produced from the plate. It was done in such a way that the fusion line of copper with steel was located in the middle of sample test portion. During tests the failure took place along copper (Figure 9).

This indicates that a copper–steel contact strength is higher than the copper tension strength. Table 2 gives the results of mechanical tests.

Thus, mechanical properties of tested samples are higher than in strained and annealed copper following reference data.

Conclusions

As a result of carried work it was experimentally determined that the method of brazing in autonomous vacuum provides high-quality joining of copper with steels having various content of carbon and can be recommended for production of steel-copper products and bimetal billets.

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Received 27.03.2018