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PROBLEMS AND PROSPECTS OF SURFACING OF COPPER AND COPPER PARTS BY WEAR-RESISTANT LAYERS (Review)

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The prospects for application of the methods of arc and plasma-powder surfacing, in order to increase the wear resistance of copper parts, are shown, proceeding from the results of literature analysis. Selection of promising materials was performed for deposition of copper-resistant layers on copper surfaces by these methods. Comparative evaluation of physico-mechanical properties of copper and the main alloying elements of promising surfacing materials was performed. 31 Ref., 1 Table, 6 Figures.

Keywords: surfacing of copper, wear-resistant layer, increase of wear resistance, copper, dissimilar metals, weldability, fusion zone

Copper has such unique properties, as high electric and heat conductivity, ductility and corrosion resistance, which it preserves in a broad range of temperatures (−253–500 °C) [1−7]. Such properties allow widely using copper and its alloys in different industries, when manufacturing cable and electric contact products, heat exchangers, moulds, tuyeres, pipelines, chemical apparatus components, etc.

At the same time, owing to low heat- and wear resistance [8], copper has limited application in some metallurgical industries, in particular, under the conditions of contact with molten metal, high-temperature gas flows, aggressive gases and abrasive substance. Copper parts wear rapidly under such extreme service conditions. Moreover, such defects as burn-through, corrosion, cracks, etc., can form on their surfaces and welds [5−9].

In this connection, the question arises of improvement of fatigue life of copper parts, manufacturing which often involves the need to join copper and its alloys to steel and alloys of other alloying systems [3]. Proceeding from the fact that repair of units, replacement equipment and spare parts make up a considerable portion of product cost in industry [10], the question of improvement of wear resistance of copper parts, which are operating under difficult conditions of elevated temperatures and mechanical loads, different kinds of wear, corrosion and other unfavourable factors, is quite urgent now.

One of the possible solutions of this problem is creating protective deposited layers with high service properties on the copper parts. Up to now, however, mostly the questions of direct welding of copper and its alloys to steel, as well as steel surfacing by copper, bronze or brass, in order to save nonferrous metals, have been well studied [1−9]. The counterquestion on copper surfacing by wear-resistant alloys of different alloying systems, today remains practically unstudied. This is, primarily, related to great difficulties arising at deposition of alloys, having much higher melting temperature, lower heat conductivity and other physico-mechanical properties, which differ significantly from similar characteristics of copper.

Analysis of the methods to produce wear-resistant layers on copper surfaces. Questions of weldability of such dissimilar materials as steel and copper, while ensuring the required physico-chemical properties of both the wear-resistant layer, and the entire part as a whole, requires development of such technological processes, which take into account not only metallurgical compatibility, but also the difference in the physical properties of the materials being joined: heat conductivity, heat capacity, melting temperature, electric conductivity, coefficients of thermal expansion (CTE), etc. [1].

Analysis of publications [11−14, etc.] shows that thermal methods of deposition of coatings of different composition are the most often used, in order to solve this problem, and there as also scattered data on application of some solid-phase surfacing or welding methods.

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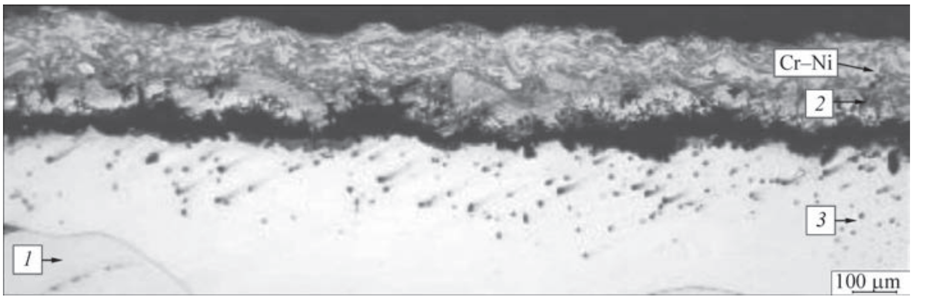

Figure 1. Microstructure of a copper sample with aluminium underlayer and Cr–Ni spraying [11]: *1* — copper base; *2* — porous layer; *3* — α-phase

So, the method of thermal deposition of coatings became rather widely applied in industry, due to its versatility, which allows applying diverse materials: metals (including refractory metals of W and Mo type), Ni and Co based metals, ceramics based on Zr oxides, etc. [15].

It was proposed to apply this process [11] also for improving the resistance of some copper parts, operating under the conditions of high-temperature gas-abrasive wear. For this purpose, layers of aluminium-containing coating 0.1–0.5 mm thick were applied on the copper surface. However, despite the fact that average resistance of parts strengthened by such a method, increased 1.5–2.0 times, an uncontrollable appearance of damage was noted, which was caused by sudden delamination of the coating in service, as a result of low strength of the produced joint and considerable difference between CTE of the coating and copper (Figure 1) [11].

In order to eliminate this drawback, the authors of [8] recommended applying additional heat treatment, during which aluminium diffuses into copper. This was supposed to increase the strength of adhesion of the coating to the base metal, and to enable producing a layer, having higher high temperature and wear resistance, compared to copper.

However, heat treatment does not always improve the strength of adhesion of the coating and copper base [11]. It is explained by the fact [5] that diffusion of coating elements into copper results in a significant lowering of their concentration in the diffusion layer and increase of the amount of brittle oxides in it that, contrarily, may promote delamination of part of this layer from the coating side.

In work [16] this phenomenon was considered in greater detail. One can see from Figure 2 that microscopic cracks are present between the coating and the base, which at long-term operation under wear come together to form fragments (Figure 2, *b*), delaminate and form plates of wear products. The authors of the same work note that delamination is a dominating wear mechanism of specimens produced by this method, and the method proper is labour-consuming and has a low productivity.

In work [17] it is noted that application of plasma method of deposition of protective coatings of different composition on a copper base allows increasing the wear resistance, compared to pure copper 1.5–3.0 times. It should be noted, however, that application of thin coatings (0.5–0.7 mm) under the conditions of gas-abrasive wear does not allow a significant improvement of the fatigue life of such parts.

It is common knowledge that surfacing methods became widely applied, both in manufacture of new and in repair of worn parts [10], as they allow a significant improvement of their fatigue life through deposition of layers of different composition, which differ from base metal by their physico-chemical properties [18, 19]. In addition, surfacing allows achieving much higher strength of bonding of the base and deposited metals, than at deposition of thermal coatings.

However, surfacing of steel exactly with nonferrous metals, and not vice versa, has been quite well studied so far. For the first case, the simplest and most effective is application of the methods of consum-

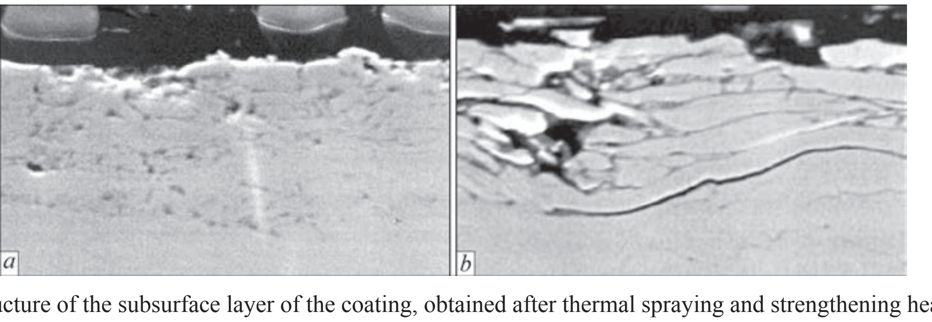

Figure 2. Microstructure of the subsurface layer of the coating, obtained after thermal spraying and strengthening heat treatment [16]: *a* — availability of microcracks under the surface; *b* — formation of plates and their delamination

able-electrode surfacing, with application of special gases or fluxes as a protective environment [9, 20].

It should be noted that the main disadvantage of arc surfacing methods is a considerable penetration depth that may lead to excess mixing of nonferrous metal with steel, and appearance of cracks and pores in the deposited layer [20]. However, despite the fact that the great penetration depth is characteristic, for instance, submerged-arc welding, it, nonetheless, is quite often used in welding copper and steel parts, 5–40 mm thick [9, 14. 21].

Gas-shielded surfacing is characterized by greater versatility. Its main advantage is the impossibility of visual observation of the process of its prompt adjustment, if required [20, 22]. Special surfacing methods, such as pulsed-arc surfacing with split or strip electrode, etc., allow reducing the penetration depth. They, however, have certain limitations as to their adaptability to manufacture, for instance, at strip surfacing of products of a complex shape [20].

At the same time, proceeding from the data in technical literature and practical experience [23, 24], it is known that in surfacing with electrodes and wires, the penetration depth can be reduced due to optimization of electric parameters of arc surfacing and application of small diameter wires (up to 2.0 mm).

It is also known that plasma surfacing is one of the surfacing methods, which ensure minimum penetration of the base metal that allows reducing the fraction of its participation in the deposited layer [4, 25, 26]. In addition, its offers the advantages of a wide range of adjustment of surfacing mode parameters, and possibility of applying a wide class of materials, as well as performance of product preheating without application of extraneous heat sources [4, 17, 25].

In technical literature, however, the data on application of both the arc and plasma surfacing to strengthen the surfaces of parts from pure copper are quite scarce. For instance, in work [26], a methods of plasma surfacing of aluminium bronzes with cobalt and nickel alloys is described. Practically the only mention about the methods of pure copper surfacing with steel and alloys is found in works [17, 27], which describe the method of producing protective layers 1.5–2.0 mm thick by electron beam surfacing. When this method is used, good adhesion of the protective material based on refractory metal carbides to the copper surface has been achieved, while the fatigue life of parts with such strengthening increased up to two times.

At the same time, this method has certain disadvantages. In addition to rather complex and rather expensive equipment, during deposition part of the powder being deposited does not reach the weld pool [27]. In order to solve this problem, the authors of work [27] made cardinal changes in the technology of electron beam surfacing: at the first stage, flame spraying of the coating was performed, which was then melted by the electron beam. However, such additional operations made the deposition process even more complicated and increased the probability of appearance of different defects in the surfaced product.

We should separately mention such special methods of producing a steel-copper bimetal joint, as explosion welding, pressure welding with preheating, friction stir welding, high-temperature synthesis, etc. [12, 13, 17, 28]. Despite the fact that these methods allow making a rather reliable joint, their application to produce wear-resistant layers is often essentially limited by the geometrical dimensions and shapes of the parts proper. In addition, they also have their disadvantages, for instance with the detonation method, air voids can form on the joint boundary that may lead to erosion failure of the coating or its spallation [13].

Selection of wear-resistant materials for deposition on copper surfaces. Proceeding from the data of literature analysis, we can single out several classes of materials, which are suitable for the above-mentioned service conditions [10, 25]:

- heat-resistant steels, complexly alloyed by chromium, molybdenum, nickel, etc.;
- high-carbon high-chromium iron-based steels (Sormite type);
- alloys on nickel or cobalt base.

Heat-resistant steels of Fe–C–Cr–Mo–V alloying system are widely used for strengthening metallurgical equipment components, operating under thermal cycles, and high dynamic loads, in combination with abrasive wear. Steels with a high tungsten content have the highest hardness and heat resistance at high temperatures. However, thermal stability and impact toughness of such steels is comparatively low [10]. Tungsten replacement by molybdenum (complete or partial) lowers the heat resistance of the steel, but essential increases its thermal stability. Steels of this

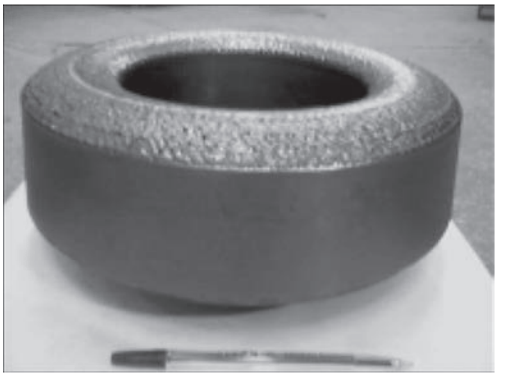

Figure 3. Appearance of the tuyere head of a blast furnace, surfaced by electron beam method [27]

class are prone to cracking at surfacing, so surfacing is performed with preheating and sometimes concurrent heating.

High-carbon high-chromium steels with carbon and chrome content up to 5 and 30 %, respectively, are widely applied for surfacing parts operating under the conditions of intensive wear at high temperatures (up to 1000 °C) [10]. Different methods can be used for surfacing by these materials. However, surfacing technology is associated with considerable difficulties, in connection with prevention of cracking. Preheating and concurrent heating of the part up to 600 °C are mostly used for this purpose, and after surfacing the part is placed into a furnace heated up to the temperature of 650−700 °C and slowly cooled together with it.

Nickel-based alloys have high high-temperature resistance, high thermal fatigue resistance, high resistance against different kinds of corrosion and low susceptibility to cracking at surfacing. Some of the most common grades of this type of alloys are Hastalloy and Inconel of alloying systems of Ni–Cr–Mo–Nb type [10]. By the data of numerous studies [6, 7, 21, 27, and oth.], application of materials, alloyed with nickel, allows producing metal with better indices of weldability, corrosion and wear resistance. In addition, by some data [21], additional alloying with nickel at cast iron surfacing by copper alloys promotes a more uniform distribution of base metal in the deposited metal without formation of individual iron inclusions in the upper layer of copper.

Cobalt-based alloys of Co–C–Cr–W alloying system are characterized by high wear, high-temperature and corrosion resistance, etc. in many aggressive media [10]. Hardness of such alloys at temperatures above 650 °C in higher than that of nickel-based alloys. The main disadvantage of cobalt alloys is their high cost, as well as cracking susceptibility.

In terms of weldability, mutual solubility of the main alloying elements of steels and alloys, mentioned above, as well as copper, is important. Constitutional diagrams of the respective binary systems are given in Figure 4 [29].

1) Carbon. Constitutional diagram of Cu−C state (Figure 4, *a*) shows that copper is in equilibrium with carbon in the solid and liquid state. Carbon solubility in liquid copper in wt.% is as follows: 0.0001 at 1100 °C; 0.00015 at 1300 °C and 0.003 at 1700 °C. There are data that near the boiling temperature copper dissolves up to 1 wt.% (5 at.%) C, which precipitates from the solution in the form of graphite even at rapid quenching [29].

2) Iron. Copper forms a solution with iron with up to 3.0 % iron solubility in molten copper up to the temperature of 1025 °C (Figure 4, *b*). Copper solubility in γ-Fe at temperatures of 1470, 1370 and 1100 °C is equal to 10.0; 12.0 and 8.0 at.%, respectively. In this system two peritectic and one euitectoid equilibria are in place, and at strong overcooling (overcooling degree of 100 °C and higher) an area of nonmixing in the liquid state appears. Critical mixing temperature is 20 °C below the liquidus temperature at equiatomic bonding [29].

3) Nickel. Among structural metals, only in Cu–Ni system its component metals have unlimited mutual solubility, and are characterized by formation of a continuous row of solid solutions (Cu, Ni) with face-centered cubic structure during crystallization (Figure 4, *c*). There are also some calculated data on the availability of the separation boundary of the solid solution and critical point of nonmixing, which correspond to Ni concentration of 69.7 at.% and temperature of 342 °C and are related to magnetic transformation of Ni [29].

4) Cobalt. Cu−Co system (Figure 4, *d*) is a diagram of peritectic type. Eutectoid transformation is in place in the solid state. Maximum solubility of copper in α-Co is achieved at the temperature of 1367 °C and is equal to 19.7 at.%. In alloys of Co–Cu system strong overcooling (by 100 °C and more) results in appearance of an area of nonmixing in the liquid state, which is almost symmetrical relative to the joint axis. At equiatomic bonding, the critical mixing point is located 90 °C below the liquidus curve [29].

5) Chromium. In keeping with Cu−Cr constitutional diagram (Figure 4, *e*), this system demonstrates the presence of a eutectic equilibrium and existence of two solid solutions based on Cu and Cr. However, the nature of phase-equilibria in the high-temperature region at concentrations of 0−55 at.% Cu is ambiguous. It is believed that monotectic equilibrium at the temperature of 1767±8 °C and concentration of 18.8 at.% Cu is in place in the entire concentration range in alloys containing from 4 up to 45 at.% Cu. The area of separation of the two liquids extends from 18.8 to 45 at.% Cu in a narrow temperature range, the upper limit of which is not higher than 1900 °C. Also confirmed is the existence of a two-phase region (liquid + Cr) in the concentration range of 42−97 at.% Cr at the temperature of 1550 °C. Maximum solubility of chromium in copper at the temperature of 1076.6 °C is equal to 0.89 at.% [29].

6) Molybdenum. Constitutional diagram of Cu–Mo was not plotted experimentally, due to the fact that Cu and Mo do not mix in the liquid and solid state, while mutual solubility of the components at the temperature of 900 °C is extremely small. Therefore, the constitutional diagram of this system, which is shown in Fig-

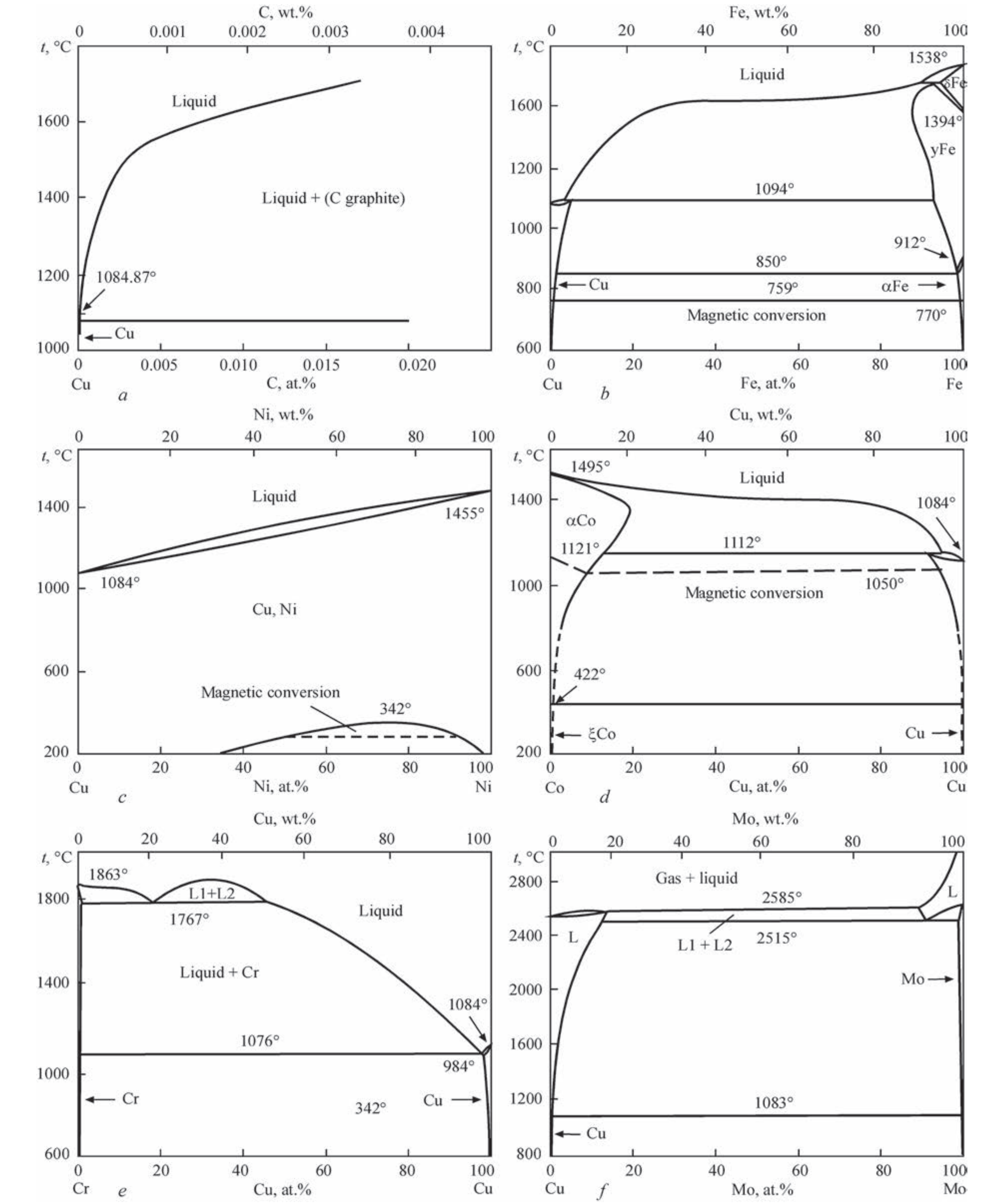

Figure 4. Constitutional diagrams of Cu–C (*a*), Cu–Fe (*b*), Cu–Ni (*c*), Co–Cu (*d*), Cr–Cu (*e*) and Cu–Mo (*f*) binary systems [29]

ure 4, *f*, was derived exclusively by calculation methods, in keeping with which the monotectic and eutectic equilibria are in place in the system. Mo solubility in Cu is equal to 1.91 and 2.50 at.% at temperatures 1900 and 2100 °C, respectively, and Cu solubility in Mo is equal to 2.3 at.% at the temperature of 950 °C [29].

In view of the above-said, quite promising are the ideas on copper surfacing by wear-resistant alloys based on iron, nickel or cobalt, complexly alloyed by other elements, which have high mutual solubility with copper. This should promote reduction of chemical inhomogeneity and lowering of the probability of precipitation of individual inclusions, both in the base and in the deposited metal.

Problems of weldability of alloys based on iron, nickel and cobalt in welding with copper. Considering the possibility of deposition of wear-resistant alloys on the copper base, it should be noted that by some data [30], in copper welding to steel, application of increased content of iron powder leads to negative impact on the quality of the produced joint. This is caused by higher concentration of iron dendrites on the fusion boundary that, on the one hand, ensures an increase of weld hardness and its strength, but at the same time reduces weld ductility, leading to defect formation in it, thus lowering the service properties of the welded joint [21].

At the same time, copper joint with nickel can be relatively easily produced by the methods of fusion welding without filler or with a filler of copper, nickel, and copper-nickel alloys [1–3]. The fusion boundary of such a joint is clear-cut and has well-defined transition layers. However, in keeping with the data of work [3], this is not regarded as a disadvantage, as the strength of this joint is rather high and fracture runs beyond the fusion zone.

In order to assess the weldability of alloys based on iron, nickel and cobalt with copper, it is necessary, first of all, to compare their main properties (Table).

One can see from the Table, that the essential difference in some physical properties of these metals can impair their weldability. In addition, higher oxidation of copper and considerable absorption of gases by it have a negative effect on weldability [4].

By the data of [4, 9, 22], the following main factors can be singled out, which affect the weldability of alloys based on iron, nickel and cobalt with copper:

- high heat conductivity of copper that leads to high cooling rates and need to apply the welding heat sources with very high heat input, or considerable temperatures of preheating and concurrent heating, and most often both the one and the other;
- much lower temperature of copper melting;
- short time of weld pool existence in the liquid state that limits the possibilities of its metallurgical processing and requires active deoxidizers;
- considerable CTE of copper that makes more complicated fastening and preservation of the position of the parts during welding, and that determines the need to take additional measures against the structure deformation;
- high fluidity of copper that limits the used positions of the parts being surfaced, and, for instance during deposition of circular beads in surfacing cylindrical parts;
- significant impact of impurities on copper properties and weldability that requires application of metal with strictly regulated content of oxygen, bismuth, lead, sulphur and antimony;
- high sensitivity of copper to hydrogen, that requires taking special measures to lower its content in the welding zone, in order to prevent porosity;
- light oxidation of copper in the molten state which leads to formation of low-melting eutectics that lowers the weld metal resistance to solidification cracking.

Under the impact of these factors, several main problems are singled out which are characteristic for welding copper and the above-mentioned alloys: formation of hot cracks, including those filled by nonferrous metal; formation of brittle interlayers, as well as significant interpenetration on copper-alloy boundary [1–3, 20]. The data given below disclose the outlined problems in greater detail. However, they mainly concern welded joints of copper-steel type or cases of copper deposition on steel, as the questions of fusion welding of copper with alloys on nickel and cobalt base are hardly covered in technical literature.

By the data of work [2], in welding copper to steel, at increase of copper content in the weld metal above 3 %, the hot cracking susceptibility rises abruptly. In this case, at solidification of weld metal, copper, owing to limited solubility in steel, precipitates on the grain boundaries, and cracks form under the impact of tensile stresses and Rebinder effect.

Initial penetration of copper along the steel grain boundaries that proceeds under the impact of the capillary effect, diffusion and dissolution of steel in copper, is further facilitated by that the surface energy on Fe–Cu boundary is approximately two times smaller

Comparison of crystallographic and physical properties of pure copper, iron, nickel and cobalt [31]

Characteristic	Cu	Fe	Ni	Co
Atomic mass	63.54	55.85	58.69	58.93
Crystalline lattice type	f.c.c.	γ – f.c.c.; α – b.b.b.	f.c.c.	f.c.c.
Melting temperature, °C	1083	1535	1453	1494
Boiling temperature, °C	2310	2450	2732	2960
Coefficient of thermal expansion by 1 °C, 10^{-6}	17.06	12.15	13.6	12.5
Heat conductivity, W/(m·K)	413	94	107	122
Specific heat capacity, J/(kg·K)	385	449	500	244
Specific electric resistance, Ohm·m, $\cdot 10^{-8}$	1.68	10.0	6.99	5.68
Density, kg/m^3	8930	7850	8900	8900

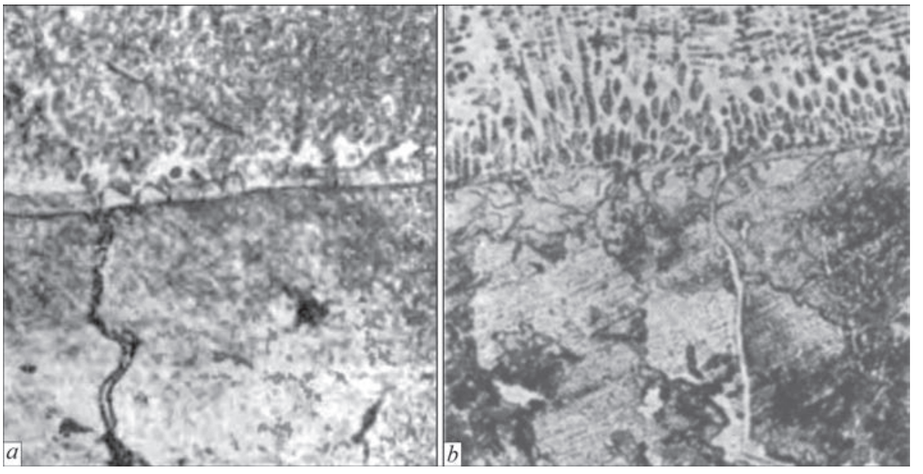

Figure 5. Fusion zone in argon-arc spraying of Br. A5 bronze on St3 steel (*a*) and Br. ANZh6-3-1 bronze on steel 20 (*b*), ×300 [2]

than that on Fe–Fe boundary. Therefore, the strength on grain boundary, which is in contact with liquid copper, turns out to be lower, and tensile stresses, developing in the metal, are sufficient for final rupture of the weakened boundary and instantaneous filling of the newly formed crack by copper (Figure 5). Nonferrous metal penetration into steel to the depth of more than 2.5 mm in some cases lowers the static, and particularly, fatigue life of steel [2]. Alongside cracks in the usual sense, defects of the type of «healed» cracks completely filled with copper or copper alloy, are characteristic for steel surfacing with copper.

In order to eliminate these defects, in work [3], it is proposed to add a certain amount of aluminium to the weld pool. In this case, the produced welded joints of copper with low-carbon steel had higher values of mechanical properties in the presence of aluminium in the weld, compared with the respective characteristics without aluminium. Moreover, aluminium addition to the weld pool was favourable for the structure of the weld metal and near-weld zone.

Weldability of copper with steel impairs formation of brittle interlayers in the near-weld zone on the fusion boundary (Figure 6). Their formation and development are associated with diffusion of some elements from steel into copper. In order to prevent formation of interlayers of this type, it is recommended to perform preliminary deposition of layers from alloys, which reduce the possibility of formation brittle interlayers and iron transition into copper and vice versa [2].

Studying the physico-mechanical properties of welded joints of copper-low-carbon steel, exposed to variable temperatures in service, showed [14] that at up to 2 % mass fraction of iron, the weld metal strength is equal to that of base metal (copper) in the entire testing temperature range. Iron content in copper above 7 % leads to an abrupt lowering of the joint ductile properties that may lead to hot cracking. Complex evaluation of mechanical properties, long-term strength, thermal cycle fatigue and fracture mode showed that when welded joints of copper-low-carbon steel are exposed to increased and variable tem-

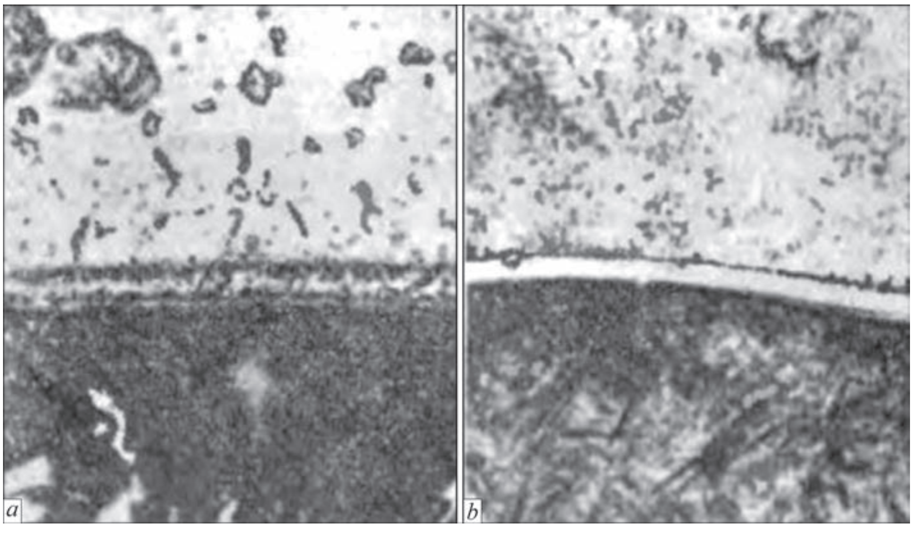

Figure 6. Brittle interlayers in the fusion zone at plasma surfacing of steel 20 with Br.AMts9-2 bronze (*a*) and of 38KhNMA steel with Br. KMTs3-1 bronze (*b*), ×300 [2]

peratures in service, 3–6 % iron content in the weld metal is optimum [14].

As to the depth of copper-steel interpenetration, according to the data of [2], the admissible penetration depth, which does not affect the mechanical properties of steel, is limited by 0.3−0.5 mm. By other data [3], however, copper alloy penetration into high-strength steel to the depth of up to 1.2 mm practically does not affect the static and cyclic strength under tension, static and impact bending of bimetal samples.

Problems of surfacing copper with alloys based on iron, nickel and cobalt and methods of solving them. Considering the possibility of deposition of wear-resistant layers on a copper base, the above-mentioned problems, arising when producing the steel (alloy)-copper welded joint, are complemented by problems caused by the technological features of running of such a process.

Firstly, as was noted earlier, this problem remains practically unstudied today — known are just a few cases of mentioning the methods of electron beam surfacing of copper with different grades of steel in technical literature. These results, however, do not always look valid or economically justified.

Secondly, all the known wear-resistant steels and alloys have much higher melting temperature, than copper (≈1500 °C against ≈1100 °C). At first glance, this should lead to increased penetration of copper. However, due to the high heat conductivity of copper (more than 4 times higher than that of steel — see the Table), the drops of molten deposited metal can quickly loose heat that will lead to an abrupt lowering of fluidity and wettability, and, hence, to poor formation of the deposited metal on the copper surface, or even to absence of formation and fusion. It is well known [9] that in butt welding of steel sheets, copper backing is quite often used in production, in order to ensure complete penetration and good formation of the reverse surface of the weld. After welding is over, this backing is rather easily removed and does not have any traces of adhesion to the weld.

In addition, due to its higher heat conductivity, copper will heat very quickly during surfacing, that increases the probability of overheating and subsequent through penetration of the copper base.

Thirdly, the above differences in the physical properties of steel and copper will lead to high temperature gradients and high cooling rates, as well as a short time of staying of the weld pool in the liquid state. This may lead to appearance of individual copper inclusions at weld pool solidification that further on lower the deposited metal performance.

In view of the absence of any recommendations in the technical literature on the features of running of the process of pure copper surfacing with nickel and cobalt alloys (as with iron based alloys), we can only proceed from the data on physico-chemical properties of these metals, considering the fact that both nickel and cobalt, similar to iron, differ greatly from copper by their melting temperature and heat conductivity. Therefore, at copper surfacing by the above alloys, the above-mentioned regularities will be true for them to a certain extent, as they were determined for the cases of copper welding to steel and surfacing of copper and its alloys with steel.

Solving all the above-mentioned problems requires a thorough and substantiated selection of the surfacing technique and technology, surfacing materials, as well as staying within a rather narrow temperature range of preheating and concurrent heating of the copper parts. In view of the foregoing and practical experience, such surfacing methods as gas-shielded arc surfacing with wires of the respective alloying, as well as plasma-powder one by alloys based on iron, nickel and cobalt, look promising.

Here, application of technological measures reducing the penetration and fraction of base metal in the deposited metal, as well as adjustment of energy input of surfacing, can have a positive effect on the quality of fusion of the wear-resistant layer and the copper base. At arc surfacing, the most widely spread in industry, this can be achieved through application of small-diameter electrode wires (1.2−2.0 mm dia); moderate electric modes, in which a stable transfer of electrode metal and minimum base metal penetration are ensured, as well as application of pulse, magnetic-pulse and other technologies. In our opinion such a comprehensive approach, on the one hand, should promote sound fusion of the wear-resistant layer with copper, and on the other hand, it should not allow overheating of the copper base that may lead to a change of the geometrical dimensions of the part.

Thus, despite considerable difficulties, arising at wear-resistant arc or other methods of copper surfacing, these processes are quite promising, in terms of ensuring a considerable extension of fatigue life of copper parts, operating under the conditions of abrasive and gas-abrasive wear, as well as wear at high-temperature friction of metal against metal.

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