Reduction of Copper to Steel Weld Ductility for Parts in Metallurgical Equipment

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ABSTRACT

Despite being challenging, the welding of the dissimilar metals copper and steel is an essential process that is required for improving quality of equipment manufacturing in the fields of metallurgy, machine construction, and chemical industry. Restricted solubility of iron in copper leads to the formation of a supersaturated solid solution of iron and other chemical elements in the weld pool. Investigations have found the possibility of enhancing the process of welding copper with steel. In the case of using a flux-cored welding wire and an improved welding technique, the number of dendritic inclusions is reduced, and the weld ductility is improved. Studying the microstructure of a copper to steel weld confirmed the ability to enhance the outcome of the welding process of the dissimilar metals. The implementation of recommended preparation techniques of parts before welding, and optimization of the welding technique will increase the strength

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of the welds and, increases the operational reliability of metallurgical equipment.

Keywords: *Copper to Steel Welding; Flux-cored Wire; Microstructure; Fusion Line; Alloy Formation*

Introduction

In order to yield high-quality weld assemblies, the method of which dissimilar metal joints are produced, and the resulting properties, plays a very important role. Maintaining such welding process under control makes it possible to produce dissimilar metal welded joints with the required indices of physic, chemical and technical properties. Such weld assemblies including dissimilar metal joints are used in metallurgy, machine construction, and chemical industry equipment manufacturing.

Process regulation is associated with a need to predict the resulting changes brought by the welding technique [1], [2]. The quality of a copper to steel weld has a great effect on the durability of a produced assembly when used under operational conditions that can cause cyclic load and thermal fatigue. This situation can be found in metallurgical equipment, for example, furnace Tuyeres and Crystallizers [1]-[3].

Both copper and iron have a face-cantered cubic lattice construction, with a relatively similar crystal lattice; for copper: a = 0.3615 nm, N = 4, and for iron: a = 0.3656 nm; N = 4(in temperatures between 910 to 1392 ºC), parameters [4]. Still some difference between them are found: a difference in melting temperatures; for copper: 1083 ºC (1356.2 K), while for iron: 1535 ºC (1808 K), a difference in their heat conductivity coefficient: for M1 copper (20 °C) it is 390 Wt/(m·K), while for St.3 steel it is 67 Wt/(m·K), and in the value of their elastic modulus: for copper 90×10^{-3} MPa, while for iron 201×10^{-3} MPa. When welding copper and steel (where the main interaction is between copper and iron), differences in their melting temperature, density, thermo-physical properties (melting temperatures, heat conductivity coefficient, and the elastic modulus) affect the joining process [2], [4].

Improvements in the welding techniques of copper and steal that will yield a joint with better properties are important. The technical parameters of a welding process can be optimized by the analysis the welded metal joint properties [4]. A copper to steel weld usually fails due to cracks and damage, both along the fusion area and within the heat-affected zone from the copper side [5]-[7].

Many welding techniques have been investigated to overcome the challenge of copper to steal welding. Kuryntsev et al. [6] explored the usage of laser welding due to the high energy density provided by this technique. Guo et al. [7] investigated the usage of electron beam welding (EBW) with great results. Brazing is also considered for copper to steal joints [8]. However, the aforementioned techniques are faced with some complications such as the ability of copper to reflect laser when laser welding, the need for a special setup for the process (welding in vacuum) in EBW, and the resulting week mechanical properties of the work peace in brazing. All are limiting factor for real-life, in site application. Arc welding is considered as the most practical technique for on-site applications because of its low cost, convenience, and flexibility [9]

One of the factors resulting in reduction of copper to steel weld ductility is an increased amount of iron dendritic inclusions within the area of alloy formation in copper side [11]-[14]. The heterogeneity of the copper to steel weld and a decrease in the ductility index, i.e. an increase in the ultimate strength and an increase in the hardness of the heat-affected zone, result in the decrease in fatigue failure along the fusion zone during cyclic loading, mainly under a symmetrical loading cycle for the structure [13]. Controlling dendritic inclusions of iron into copper lead to improved durability of the weld, and reduced fatigue failure during cyclic loading.

Analysis of the weld ductility reduction factor and analysis of the weld structure and adjustment of welding technology are essential for improving copper to steel weld quality. Therefore, the impact of increased iron content in welding materials and the volume of molten steel on the penetration depth of iron dendritic inclusions into copper is studied.

Materials and Methods

In the work presented here, both M1 copper GOST 1173-2006 (Table 1) was welded to St.3 sp.5 steel GOST 380-94 (Table 2). These comprise parts used in a metallurgical crystallizer.

For the welding process, the electrode used in shielded metal arc welding was Komsomolets-100 type (14-644-75 standard, GOST 9466-75). The welding was performed in the lower position at a reversed polarity direct current. Electrode diameter used was 4 mm, and the welding current ranged between 130-150 A, while the used filler wire was MNZhKT 5-1-0.2-0.2 in argon-arc welding of M1 copper to 09G2S steel.

Thickness of samples was 6 mm, welding current ranged between 380 and 400 A, tension was between 12 and 16 V, and argon consumption was between 80 to 90 l/h. The composition of 09G2S steel is shown in the Table 3. Additional details can be found in [15] and [16]. Finally, the flux-cored wire that was used in welding had diameters of 3.0 and 5.0 mm.

Table 1: Content of the used M1 copper, %

Additives	0.1003
Cu	99.9
Bi	0.001
Sb	0.002
As	0.002
Fe	0.005
Ni	0.002
Pb	0.005
Sn	0.002
S	0.005
O	0.05
Zn	0.005
P	0.04
Ag	0.003

Table 2: Content of the used St.3 sp.5 steel, %

Element	Content
C	0.14 to 0.22
Mn	0.80 to 0.11
Si	0.12 to 0.30
P	< 0.04
S	< 0.05
Cr	< 0.30
Ni	< 0.30
Cu	< 0.30

Table 3: Chemical composition of 09G2S steel, %

Element	Content
C	≤ 0.12
Si	0.5 to 0.8
Mn	1.3 to 1.7
Ni	≤ 0.3
S	≤ 0.04
P	≤ 0.035
Cr	≤ 0.3
N	≤ 0.008
Cu	≤ 0.3
As	≤ 0.08
Fe	96 to 97

Table 4 lists the components of the flux-cored wire PP-A-Z-F-M. An improved PDG-516M feeder with a power supply was used during welding. Rated welding current was 500A at a duty ratio of 60%. Arc voltage adjustment was between 18 to 50 V, and the welding current adjustment was 60 to 500 A.

Table 4: Components of flux-cored wire PP-A-Z-F-M, % [15]

Element	Content
Aluminium	54.1 to 60.1
Zirconium	0.8 to 0.9
Ferrotitanium	1.2 to 1.8
Copper powder	6.1 to 9.2
Hematite	3.1 to 5.0
Graphite	2.0 to 4.0
Chromium	7.0 to 9.0
Yttrium oxide	4.0 to 5.4
Fluorite	2.0 to 6.2
Sodium fluorosilicate	2.9 to 4.1
Ferromanganese	1.4 to 2.8
Ferrosilicon	1.9 to 3.4

The microstructure of a M1 copper and 09G2S steel weld joint will be studied under different welding techniques to identify the depth of dendritic inclusions penetration. In addition, a variety of electrode sizes will be tested.

Results and Discussions

The impact of iron content in welding materials on depth of dendritic inclusions within the heat-affected zone from copper side was studied. Figure 1 shows a picture of a weld between copper and steel in used in parts of a metallurgical crystallizer. As mentioned before, the welded metal was 6 mm thick.

Studying the microstructure found in the weld, it was found that an α-phase with a cubic lattice appeared within the fusion line. This phase is a supersaturated solid solution of iron in copper, where the composition of the α-phase is not constant. There indications of elements included in the composition of electrode metal, such as nickel, manganese and others [13].

To investigate the depth of dendritic inclusions resulting from crystals growing as the molten metal solidifies, the microstructure of the fusion line in a welded joint was studied. Figure 2 shows the microstructure of a welded joint between M1 copper and 09G2S steel.

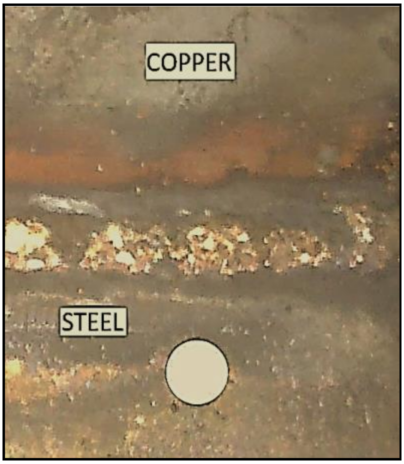

Figure 1: A weld between copper and steel used in parts of a metallurgical crystallizer

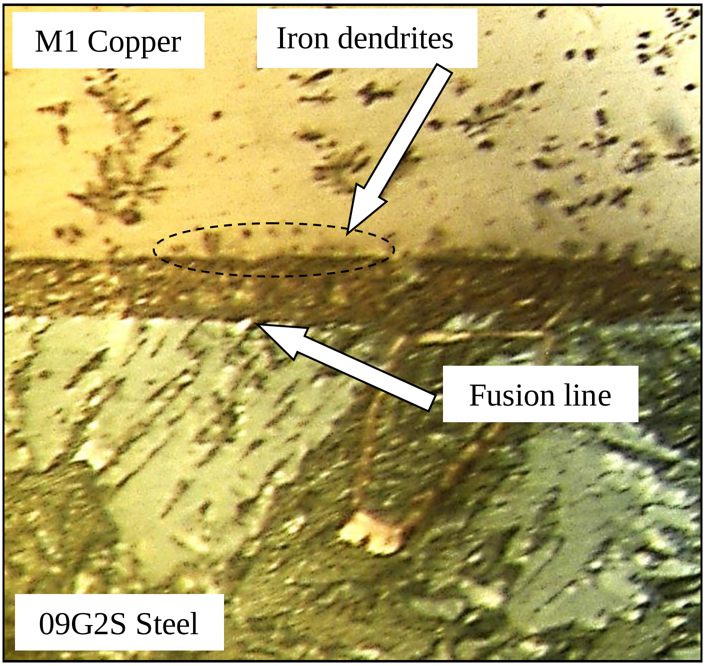

Figure 2: Welded joint microstructure, ×800 times

As it can be seen in Figure 2, iron dendrites were found next to the fusion line within the copper side (the upper side in the figure). The depth of iron dendritic inclusions penetration during shielded metal arc welding was found to be between ranging between 0.5 and 1.8 mm. The formed structures will more likely affect the properties of the equipment they are used in. Such alterations are brought by the presence of dendritic growth.

In order to examine if the application of a different approach in welding of the depth of dendritic infusion, the microstructure of a weld produced by argon-arc welding and flux-cored wire was examined. Figure 3 shows the microstructure resulting in the weld after applying the aforementioned argon-arc welding and flux-cored wire to join the two metals.

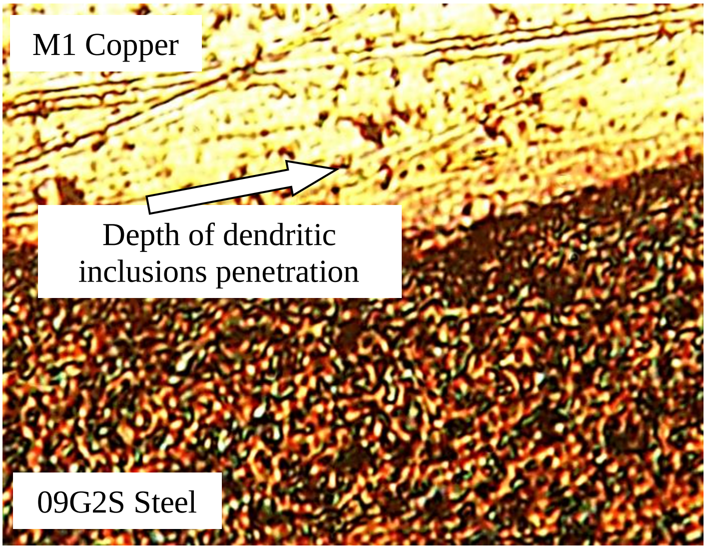

Figure 3: Microstructure of the weld after argon-arc welding, ×900 times.

As shown, it was found that during argon-arc welding and flux-cored wire welding the depth of iron dendritic inclusions penetration was found to be between 0.6 and 1.2 mm. The resulting depth compared with the depth of penetration found during the shielded metal arc welding was found to be slightly less. This indicates a slight enhancement in controlling the formation of undesired crystal structures in the final body of the weld.

Another alternative that can be employed in the welding process in order to reduce the effect of dendritic inclusions in the weld joint, is increasing the amount of welding materials used, which can be achieved by the usage of welding electrodes with larger diameters. Figure 4 shows the change in resulting depth of dendritic inclusions resulting in weld of the two metals using different electrode diameters.

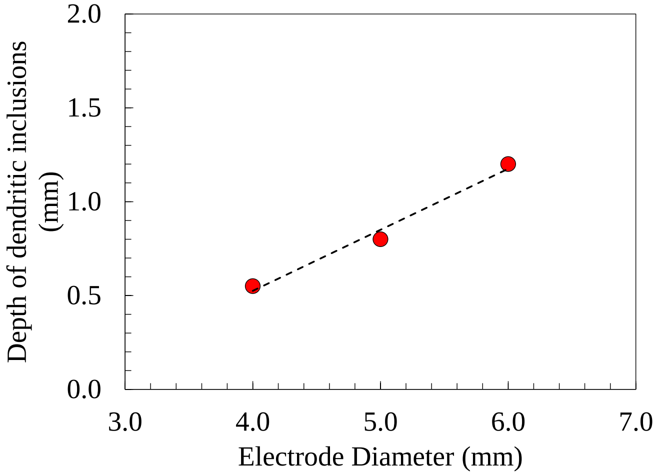

Figure 4: Dependence of the depth of dendritic inclusions on the iron content in welding materials and the diameter of the electrode

As seen in Figure 4, using an electrode with a larger diameter (i.e. increasing the welding material in the electrode) resulted in an insignificant increase in the depth of penetration. It should be noted that the resulting insignificant changes in depth of penetration, will not reduce the fatigue strength under testing for cyclic loading.

The amount of molten metal (steel) most seriously affects the amount of dendritic inclusions. The greater the extent of steel melting during the weld process, the larger the resulting weld pool. This will generate a greater specific heat input during welding, which will lead to iron crystallization not only within the weld, but also on individual grains of metal due to the limited solubility of iron in copper [17]. This occurrence can be the result of procedural violations for welding preparation. Figure 5 shows the microstructure of the weld, the fusion line, and the heat-affected zone with rejection of iron as solid solution dendrites, with increased iron melting.

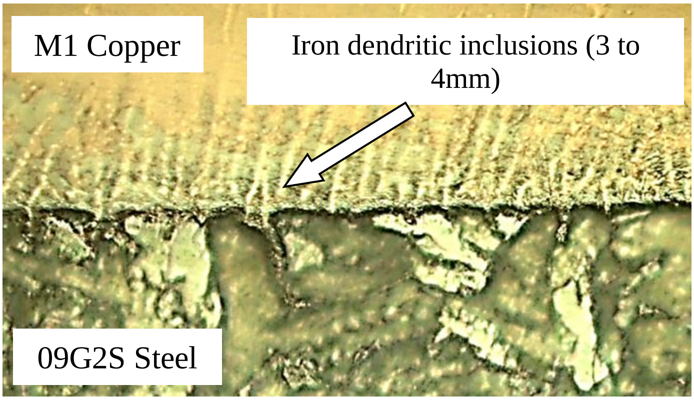

Figure 5: Microstructure of a welded joint with increased degree of iron melting

As it can be observed in Figure 5, the presence of excessive iron is kept in the α-phase as supersaturated solid solution. Such amount of iron increases the hardness of the heat-affected zone, which in its turn will reduce the ductility of the resulting weld. Resulting in a weld joint that is vulnerable to fatigue under stress. Excess iron melting could have additional consequences in the presence of other chemical elements. Figure 6 shows the welded joint microstructure in case of excess iron melting.

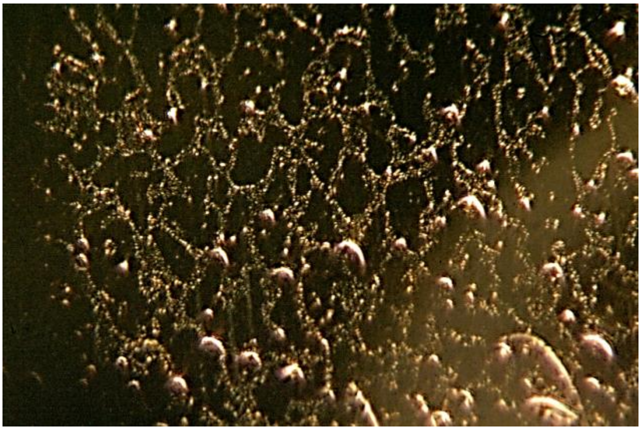

Figure 6: Welded joint microstructure in case of excess iron melting, ×800 times.

As clearly shown in Figure 6, the dendritic inclusions on the edges of the grains are in a ball-shaped form. This is where chemical elements (manganese, nickel, titanium, copper, etc.) are transferred after the diffusion. The presence of chemical elements can be attributed to failure to comply with the requirements of edge preparation before welding.

It can be deduced that excess iron melting, which occurs due some procedural violations during welding and failure to comply with the requirements of edge preparation, are the key factor of reduced weld ductility and fatigue strength of copper to iron welds.

Overall, by using an improved copper to steel welding technique and the developed flux-cored wire (controlling the weld phase composition), the number of dendritic inclusions can be reduced at the weld line. This will result in increasing the weld ductility and the durability of the weld assemblies [13], [15]-[19].

Conclusions

1. Iron content in the weld material for welding copper and steel is not the key factor that reduces the life of welded joints due to fatigue.
2. Restricted solubility of iron in copper leads to the formation of an α-phase as supersaturated solid solution of iron and other chemical elements in the weld pool.
3. If the recommendations for parts preparation before welding were followed, the fatigue strength of welded joints will not be reduced, and the operational reliability of metallurgical equipment assemblies can be improved.
4. By optimizing the composition of welding materials and the welding technique, the amount of molten iron and the degree of melting of iron in the weld pool can be reduced.

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