Optimizing the Ag Filler Metal Content on Brazing of Cu-Stainless Steel Pipes Joints for Carbon Dioxide Refrigeration Plants

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Abstract. A carbon dioxide refrigeration plant is characterized by reaching maximum temperatures in the order of 150 °C, and maximum pressures in the order of 130 bar, which means that the materials used in the pipes, as well as the connections, must present high resistance, so as not to cause disturbances in the refrigerant fluid. To make these connections, brazing and TIG welding are the processes normally used in copper-copper, copper-carbon steel, and copper-stainless steel connections, optimizing their parameters, in order to create defect-free joints. In this work copper-stainless steel joints were produced by brazing, using brazing alloys with differing silver contents, 56% and 34% respectively. The microstructure of the produced joints was analyzed and characterized, evaluating the influence of silver content on joints' quality. It was concluded that the joints obtained by using a brazing alloy with lower content of silver presented less defects and an overall better quality.

Keywords: Brazing · Silver content · Copper – stainless steel joints

1 Introduction

The joining of certain metal alloys remains as a huge challenge for researchers involving welding, but also similar processes, such as brazing and even adhesive bonding. In terms of welding, the microstructure and properties of some materials have led to systematic studies focused on obtaining the best properties in the joints, overwhelmingly well-known problems, but difficult to overcome [1–3]. Bonding with structural adhesives has also undergone considerable evolution in the last two decades. Brazing is no exception, and numerous studies are known in this area with a view on bringing the properties of the joint closer to those of the base materials [4]. The joining of dissimilar materials has deserved special attention from researchers, given the high interest of the market in this type of connection, in order to meet different properties needed in different areas of the same component. Any of the aforementioned joining techniques allow the joining of dissimilar materials, however, each presenting distinct challenges.

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Some of the most studied materials in terms of brazing are Cu alloys and stainless steels, as these alloys are widely used in various applications related to heat and transport of fluids that can be corrosive, such as air conditioning installations. Alloys used as filler metals invariably contain some silver, which has also been studied by several researchers, as briefly described below. Effectively, Deng et al. [5] used vacuum brazing to joint graphite and stainless steel, using an Ag-Cu-Ti alloy as filler metal. Dense, defect-free joints were achieved when using a brazing temperature of 950 °C, with holding time of 10 min at that temperature. The joints showed excellent electrical conductivity, in addition they exhibited a shear strength of about 27 MPa. Paidar et al. [6] studied the brazing of IN617 and AISI 321 SS alloys. Using a constant temperature of 750ºC and two holding times at that temperature, those researchers verified that the maximum shear strength (322.9 MPa) was achieved using 60 min of brazing time. On the other hand, it was also found that the AMS4772 silver alloy with a thickness of 50 μm in the bonding layer is an excellent option for this dissimilar bond. Mangla et al. [7] also studied the joining of stainless steel to oxygen-free copper alloys by vacuum brazing using the 68Ag27Cu5Pd alloy as filler material. The process took place at 920 ºC for 10 min, verifying a slight diffusion of the filler metal to the base materials. The joint had very good quality and no larger cracks were observed, being considered as a hermetic joint. Zhang et al. [8] used vacuum brazing to bond martensitic stainless steel to tin bronze using as filler material an Ag-28Cu alloy at 850 °C for 12 min. Cu-based and Ni-based solid solution phases were identified between filler metal and the Ni layer, which contributed positively to the shear strength. The subsequent annealing process gave rise to a brittle intermetallic compound ($FeNi_3$), which was at the origin of cracks during deformation caused by shearing forces. Nishi and Kakuchi [9] studied the brazing of stainless steels with a dispersion-strengthened copper alumina using four different types of filler metal: one silver-base (BAg-8) filler metal and three gold-base (BAu-2, 4, 11) ones. It was observed that the smallest grain size was obtained in the samples bonded with BAu-2, BAu-4 and BAu-11, respectively, which is also consistent with the temperature level used in the brazing process. Joints brazed with BAu-2 filler metal, also presented the best mechanical strength. Li et al. [10] studied how to improve the microstructure and mechanical strength of brazed joints between Cu and stainless-steel alloys using two similar joints but with their interfaces oriented at 90° and 45° with respect to the applied load. A considerable discrepancy was noted between the calculated and obtained mechanical strength for each of the situations, due to the way the geometrically necessary dislocations are stacked.

The use of silver alloys has also been extensively studied in brazing, not just in the Cu/stainless steel bond [11–14]. Hao et al. [11] studied the microstructure and mechanical behavior of $FeNi_{42}$ alloy and SiC ceramic vacuum brazed joints, successfully using Ag-27.3Cu-2.5Ti wt.% at 880 °C. On the other hand, Guo et al. [12] used Ag-Cu/Ag/Mo/Ag/Ag-Cu-Ti multilayer as filler material to successfully braze Si_3N_4 to AISI 316L stainless steel. Kumar and Gandhinathan [13] used the BAg22 alloy for brazing Ti to stainless steel. Zhu et al. [14] used Ag–Cu alloy to braze high nitrogen austenitic stainless steel and 316L austenitic stainless steel. An alloy composed of Ag-Cu-Ti was also used to joint IN738 to SiC ceramic [15]. However, no studies were found in the literature that aimed to study the influence of the silver content on brazing.

2 Materials and Methods

In the present section the various materials and methods that were used to develop the conducted work are going to be presented, starting with the presentation of the different base materials and brazing alloys.

2.1 Materials

As for the based materials used for brazing, these were four, namely: AISI 304, AISI 316L and Copper alloy K65. Regarding the chemical composition (%wt) for each of these alloys, the AISI 304 stainless steel has a composition of: 19.5% Cr, 10.5% Ni, 2.00% Mn, 1.00% Si, 0.11% N, 0.07% C, 0.05% P and 0.03% S. The AISI 316L stainless steel has a composition of 18.5% Cr, 13.0% Ni, 2.00% Mn, 2.50% Mo, 1.00% Si, 0.11% N, 0.045% P, 0.03% C and 0.02% S. Finally, the copper alloy K65 has the following chemical composition: 2.60% Fe, 0.20% Zn, 0.15% P and 0.03% Pb. These materials were all supplied as pipes, having a thickness of 2 mm.

Brazed joints were created, by joining the K65 copper alloy with the referred steel alloys, using two different types of brazing alloys, supplied as rods. Regarding these alloys, all the used alloys contained Ag, Cu and Zn. Brazing Alloy 1 has a chemical composition (%wt) of: 34.0% Ag, 36% Cu, 27% Zn and 3% Sn. While brazing Alloy 2 has the following chemical composition: 56% Ag, 22% Cu, 17% Zn and 5% Sn.

The brazed joints were obtained by using an Oxy-acetylene torch to melt the brazing alloy rods, thus joining the pipes made of the aforementioned base materials.

2.2 Methods

In this subsection, the employed brazing process as well as the sample analysis methodology is going to be presented. As previously mentioned, the objective of this work is to evaluate the influence of silver content on the produced brazed joints' quality.

Regarding the brazing process, the opted parameters were maintained constant for all the produced joints, varying the alloy and type of base material that was going to be joined. The chosen parameters are the following: brazing temperature of 640 °C; welding speed of 100 mm/min; using as a heat source an oxy-acetylene torch, using a gas ratio of 1.2:1.

The produced joints can be observed in Table 1, showing the pair of base materials as well as the brazing alloy employed for each of the joints.

Three samples per joint type were produced. Each of the sample's cross-section was cut and mounted in thermoset resin. After this, each of the mounted samples was subjected to grinding and polishing operations. For the grinding operations, each sample was ground with 4 types of sandpaper (having different grits), starting with a sandpaper with a grit of 200, followed by 500 grit sandpaper, then 1000 grit and finally 1200 grit sandpaper. For each step of the grinding procedure the sample is rotated 90° (in the same direction for all steps). Regarding the polishing procedure, after grinding each mounted sample is polished in two steps, the first one involves using a diamond slurry, with an average particle size of 3 μm. The second step also involves the use of a diamond slurry,

Table 1. Produced joints obtained by brazing, showing base materials and brazing alloy

Joint	Base material 1	Base material 2	Brazing alloy
J1	AISI 304	Cu K65	Alloy 1
J2	AISI 304	Cu K65	Alloy 2
J3	AISI 316L	Cu K65	Alloy 1
J4	AISI 316L	Cu K65	Alloy 2

albeit with finer particles, having 1 μm of average particle size. Each of the polishing steps has a rough duration of 15 min.

After preparation the samples are ready for microstructural analysis, this analysis was performed by Scanning Electron Microscopy (SEM), using a FEI Quanta 400FEG-SEM equipment (Field Electron and Ion Company, Hillsboro, OR, USA), provided with an EDAX Genesis X-ray spectroscope (EDS-energy dispersive spectroscopy), having a resolution of 1.2 nm. This analysis was performed to evaluate the welded joint, by identifying the welding defects, characterize the weld zone and evaluate the influence of silver (Ag) content on the weld quality for the various produced joints. EDS analyses were performed to confirm the presence of these elements distributed throughout the welded zone.

3 Results and Discussion

Here the obtained results, regarding the characterization of the produced brazed joints are going to be presented. The results will be divided into 3 subsections, presenting the two produced joint types (using brazing Alloy 1 and 2) for each of the considered steel alloys (AISI 304, AISI 316L) joined with the K65 copper alloy.

3.1 AISI 304/K65 Brazed Joints

Here the microstructural analysis of the AISI 304/K65 brazed joints, using brazing Alloy 1 (34% Ag content) and Alloy 2 (54% Ag content) are going to be presented.

In Fig. 1 a) and b), the microstructure of the AISI 304/K65 brazed joint, using brazing Alloy 1 can be observed. Analyzing Fig. 1 a), different areas can be observed in the welded area, the lighter one, which is mostly composed by Ag, the grey one is composed by mostly Zn. It was also identified a "mixture zone" near the steel interface, composed by a mixture of Fe and Ag. Additionally, some Fe particles were observed to be distributed throughout the welded area, even being encountered near the copper interface. The "mixture zone" and the Fe particles can be observed in more detail in Fig. 1 b). The presence of these elements was confirmed by performing EDS analyses.

Regarding the weld quality, no major defects were identified in the brazed AISI 304/K65 joints, using brazing Alloy 1. Some voids were identified, but the presence of these defects may be attributed to errors occurring during the brazing process (since it is a manual one).

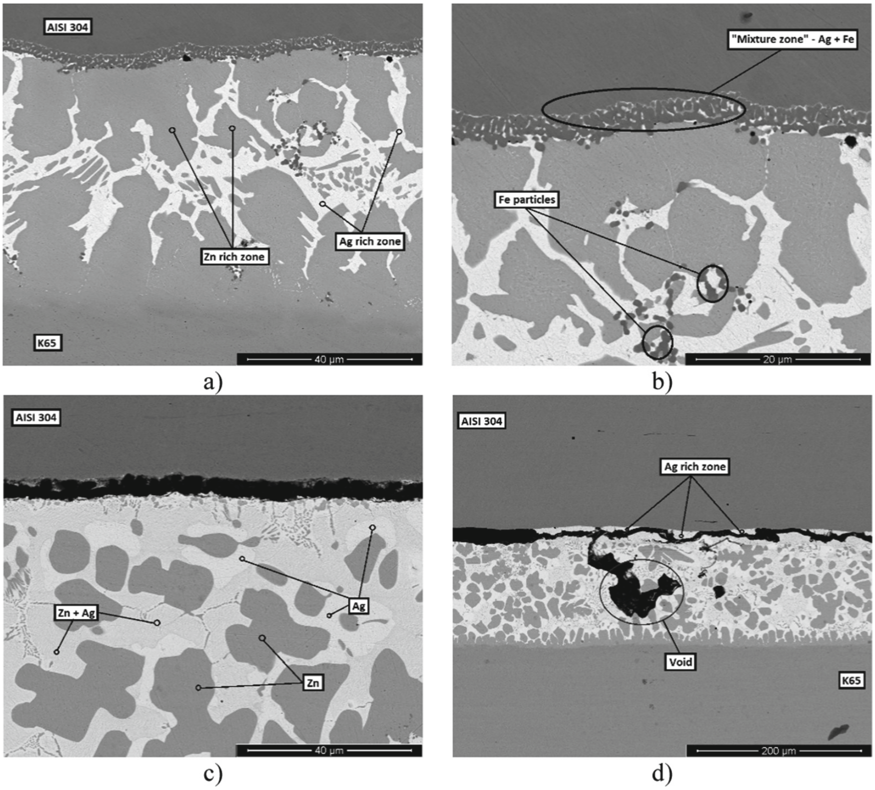

Fig. 1. SEM image of the AISI 304/K65 brazed joint, using brazing alloy 1: a) 2,500x magnification of the welded area; b) 5,000x magnification, showing the mixture zone and Fe particles; SEM image of the AISI 304/K65 brazed joint, using brazing alloy 2: c) 2,500x magnification showing the different welded area zones; d) 500x magnification of the weld defects.

The same analysis was performed for the AISI 304/K65 joints, using brazing Alloy 2 (with 54% Ag content). In Fig. 1 c) and d) the microstructure of this zone can be observed.

There are 3 distinct zones in the weld, one composed mainly of Ag (lighter zone) and other, mainly of Zn (grey zone), and an intermediate zone composed of Zn + Ag (with a higher silver content than zinc), this can be observed in Fig. 1 c). However, this type of joint presented much more defects when compared to the produced with the brazing Alloy 1. These defects were predominantly voids and lack of weld near the steel interface, as observed in Fig. 1 d). Note that there are some parts of the joint that joined to the steel, these being composed mainly by Ag. However, there is no clear evidence of a "mixture zone" registered for these joints.

As seen in the brazed joint produced with brazing Alloy 1, the presence of Fe particles scattered throughout the weld zone of these joints were also identified for the brazed joints using the brazing Alloy 2.

3.2 AISI 316L/K65 Brazed Joints

As in the previous subsection, here will be presented the two joint types produced for the brazing of AISI 316L/K65.

In Fig. 2 a) and b), the microstructure of the welded zone of the AISI 316L/K65 joint, obtained using brazing Alloy 1 can be observed. No major defects were identified, as seen in the joints of AISI 304/K65 obtained by using Alloy 1. There is no clear evidence of a "mixture zone" as seen in the previously analyzed joints, however, the adhesion is quite satisfactory, with the joint not presenting areas that lack welding. Figure 2 a) shows the weld microstructure near the steel interface and Fig. 2 b) near the copper interface. There seems to be, again, 2 main areas in the weld, ones mostly composed by Zn (grey areas) while the others are mostly composed by Ag (lighter/white areas). In addition to this, Fe particles were identified throughout the welded area, however, these were slightly bigger than those registered for the other stainless-steel joints.

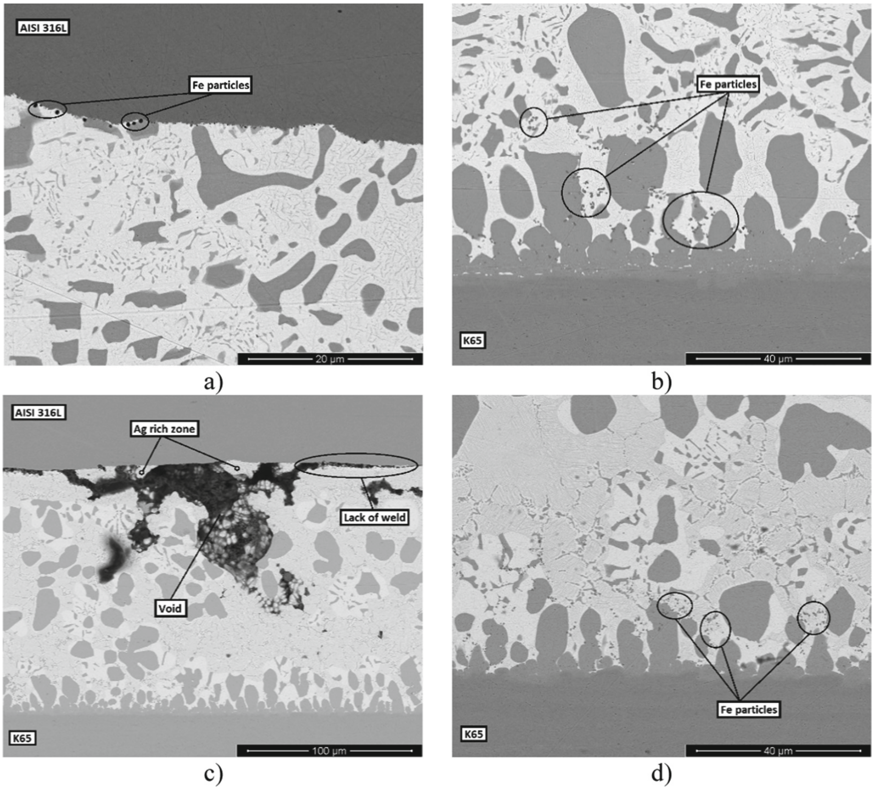

Fig. 2. SEM image of the AISI 316L/K65 brazed joint, using brazing alloy 1: a) 5,000x magnification of the welded area near AISI 316L steel interface; b) 2,500x magnification of the welded area near the copper interface; SEM image of the AISI 316L/K65 brazed joint, using brazing alloy 2: c) 1,000x magnification showing microstructure of the welded area; d) 2,500x magnification of the welded area near the copper interface.

As for the AISI 316L/K65 joints obtained using the brazing Alloy 2, it was found that, as seen in the AISI 304 stainless steel joints, the larger Ag content has a negative effect on weld quality. The weld microstructure can be observed in Fig. 2 b) and c), being again divided into two main zones, one rich in Zn and other rich in Ag. Regarding welding defects, it was registered the presence of voids and areas in which there was no weld (near the steel interface) (Fig. 2 c)). Although these defects were registered as well in the AISI 304 stainless steel joints, the severity of these in the AISI 316L joints was lesser. Regarding the quality of the weld near the copper, as seen in the previously produced joints, the brazing alloy had a good connection with the copper.

4 Conclusion

The influence of Ag content was evaluated for brazed copper-stainless-steel joints, testing two types of stainless-steel alloy (AISI 304 and AISI 316L) and two types of brazing alloy (34 and 54% Ag). The joints were produced and analyzed by SEM to characterize the quality of the welded joints. The following conclusions were drawn:

- Silver content influences the quality of both stainless-steel-copper joints welds;
- The microstructure of all the produced joints can be divided into two main parts, one mainly composed by silver (lighter areas), while the other is mostly composed by zinc (grey areas in the welded zone);
- A "mixture zone" near the steel interface was identified in AISI 304/K65 joints, obtained by employing the brazing alloy with 34% silver content;
- The "mixture zone" was not identified for the joints of AISI 316L/K65, obtained by using the brazing alloy with 34% silver content, furthermore, there seemed to be less Zn near the steel alloy interface, when compared to the AISI 304/K65 joints;
- Brazing Alloy 1 (34% Ag) created higher quality joints for both stainless-steels;
- Iron particles were identified throughout all the analyzed joints, migrating from the stainless-steel alloys to the welded zone;
- The iron particles were found, predominantly, near the copper interface;
- The size of these iron particles was greater for the AISI 316L/K65 produced joints;
- A higher content of silver promotes a weaker weld, with the joints obtained by employing the brazing alloy with 54% silver content presenting the greatest number of defects, such as voids and lack of weld (to the steel alloy);
- There was good general adhesion of the brazing alloy to the copper alloy.

The information collected from this study may enable the brazing of these types of joints to improve, by reducing the number of defects found in tubes of air-conditioning units. Less defects results in increased efficiency and less waste production.

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