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Metallurgical reactions in the coalescence zone between a reinforcement and a base metal in reinforced brazed joints[•]

B. Zorc* and L. Kosec**

Abstract

A reinforcement wire added to a brazed joint strongly improves the properties of the joint, i.e., its strength, toughness and resistance to crack initiation and propagation. This effect, however, can be achieved only if the reinforcement wire is of a suitable shape, from an appropriate material as regards the base metal and the brazing alloy and it coalesces strongly and toughly with the base metal. The properties of such a joint depend on the reinforcement wire and not on the brazing alloy. The most favourable reinforcement shape was determined. Metallurgical reactions among the base metal, the brazing alloy, and the reinforcement were studied.

Keywords

Brazed joint. Reinforcement. Metallurgical reactions. Microstructure. Toughness.

Reacciones metalúrgicas en la zona de fundición de la armadura y el material de base en las uniones armadas por soldadura

Resumen

La armadura, añadida a las uniones fuertemente soldadas, mejora considerablemente las características de la unión, es decir, su dureza, tenacidad y resistencia frente a la formación y propagación de la grieta separada. Se puede alcanzar dicho resultado solamente si el alambre de la armadura tiene la forma apropiada, está formado con el material adecuado (acorde al material de base y la unión) y se funde de manera fuerte y tenaz con el material de base. Las propiedades de la unión mencionada, dependen del alambre de la armadura y no de la soldadura. Se determina la forma más ventajosa de la armadura y se investigan las reacciones metalúrgicas entre el material de base, la soldadura y la armadura.

Palabras clave

Unión soldada. Armadura. Reacciones metalúrgicas. Microestructura. Tenacidad.

1. INTRODUCTION

A composite brazed joint may be obtained if an addition to the brazing alloy or to the joint, which remains in solid state during brazing, i.e., it does not melt, is used. Composite brazed joints are used mainly in brazing of ceramics with metals in which case the addition prevents cracking of the joints due to different specific thermal extension of the materials brazed. The addition will reduce internal stresses in the joint, which improves its mechanical properties[1-3]. Various types of additions, i.e., plates, meshes, honeycombs, fibres, powders, of ductile metals, e.g. copper, nickel, or materials with low thermal extension, e.g. tungsten, molybdenum, carbon, are used.

In wide-gap brazing of metals, metal powder is added to the brazing alloy. It reduces fluidity of the brazing alloy and improves the mechanical properties of the brazed joint[4-7]. Major improvement of the properties of such a joint is achieved only if all the components are selected so that the initial microstructure of the brazing alloy changes and does not form a brittle netlike layer round the powder added[6] or the particles are finely dispersed during the interaction with the brazing alloy[8].

None of the methods of reinforcing brazed joints known hitherto solves the problem of their toughness, resistance to crack initiation and propagation and strength in a global way. Our previous studies showed that the addition itself of a

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reinforcement wire to the joint does not improve its properties. The inserted reinforcement wire is surrounded by a brazing alloy (Fig. 1a), the boundary between the brazing alloy and the base metal being the same as in a common brazed joint. Loads are transferred from the base metal to the reinforcement wire via the brazing alloy. In this case the reinforcement wire has no influence on the tensile strength and toughness of the brazed joint (Fig. 1a).

We hypothesised and developed a new reinforced brazed joint which simultaneously solves all the imperfections of brazed joints on metal materials[9]. It was found that the most favourable reinforcement is the one made of parallel wires with a round cross-section which has to provide strong and tough coalescence with the base metal. Only such a reinforcement essentially improves the mechanical properties of the brazed joint. It is essential that the coalescence of the reinforcement wires with the base metal occurs at a large area, which may be achieved only by pressing the test pieces during brazing. The round wire cross-section will thus transform into a flat profile, which will provide the large area of coalescence desired. The joint properties will thus depend on the reinforcement wires applied[13].

2. TESTING

The following combinations of various materials were brazed:

a) base metal: copper
   wire reinforcements: copper, austenitic stainless steel X5 CrNi 18 10 (DIN 17440),
   electrolyticly copper-clad austenitic stainless steel X5 CrNi 18 10
   brazing alloy: Cu93P7 (L-CuP7, DIN 8513), rod diameter: 2 mm.
b) base metal: carbon steel with C = 0.16% (C 15, DIN 17210), carbon steel with C = 0.34 % (C 35, DIN 17210)
   wire reinforcements: carbon steel with C = 0.06 %, (D8-2, DIN 17140-1), carbon steel with C = 0.7 % (D 70-2, DIN 17140-1), austenitic stainless steel X5 CrNi 18 10
   brazing alloy: AgCu19Zn21Cd20 (L-Ag40Cd, DIN 8513), rod diameter: 2 mm.
c) base metal: austenitic stainless steel X5 CrNi 18 10
   wire reinforcement: austenitic stainless steel X5 CrNi 18 10

brazing alloys: NiCr13P10 (L-Ni7, DIN 8513), NiCr19Si10 (L-Ni5, DIN 8513), NiCr14Fe4,5Si4,5B3 (L-Ni1, DIN 8513) - all in paste, AgCu19Zn21Cd20 - rod diameter: 2 mm.
d) base metal: austenitic free-machining sulphur-alloyed stainless steel X10 CrNiS 18 9 (DIN 17440)
   wire reinforcement: austenitic stainless steel X5 CrNi 18 10
   brazing alloy: AgCu30Zn26 (L-Ag44, DIN 8513) - rod diameter: 2 mm.

The diameters of the reinforcement wires were 0.6 mm, 0.7 mm, and 0.8 mm depending on the material used. The diameter of the base-metal rods was 25 mm.

A joint specimen was brazed in such a manner that a brazing alloy, reinforcement wires, and a flux (if required) were introduced in the joint area, i.e., between two base-metal rods, at the same time. With the nickel brazing alloys, brazing was carried out in a furnace (L-Ni7 in shielding atmosphere of decomposed ammonia, L-Ni1 and L-Ni5 in argon). With the other brazing alloys, oxyacetylene torch brazing was used. With the silver brazing alloys, L-Ag40Cd and L-Ag44, in brazing of copper and austenitic stainless steel reinforcement with the L-CuP7 brazing alloy, the F-SH1 flux (DIN 8511) was used. Copper with the copper reinforcements and copper-clad austenitic stainless steel reinforcements were brazed with the L-CuP7 brazing alloy without flux.

The required condition of the brazed joints made with the nickel brazing alloys was achieved at the second stage by subsequent pressing and flame heating in the air. In the furnace the test piece could not be pressed. The brazing alloy was in liquid state during the entire brazing process (copper with L-CuP7: 30 s at a temperature of 780 - 800 °C; steels with L-Ag40Cd and L-Ag44: 15 min at a temperature of 800 - 850 °C; austenitic stainless steel with L-Ni7: 15 min at a temperature of 1030-1060 °C, with L-Ni1: 5 min at a temperature of 1070 - 1100 °C, with L-Ni5: 15 min at a temperature of 1140-1160 °C). The compression force for copper was 25-30 N/mm^2. For steels the initial compression force was 60-66 N/mm^2 whereas for the duration of brazing a compression force of 37-43 N/mm^2 was maintained.

Joint toughness was measured at room temperature on a test specimen of 55 x 10 x 10 mm in size without a notch because the majority of the

reinforced brazed joints without coalescence between the reinforcement and the base metal (especially with nickel brazing alloys) disintegrated when a notch was made. The toughness was measured with the impact force acting in the direction of the reinforcement wires. A metallographic examination of the joints was made with light and electron microscopy.

3. RESULTS AND DISCUSSION

It has been stated in the introduction that the addition of reinforcement to the joint does not improve the mechanical properties if there is no coalescence between the reinforcement and the base metal (Fig. 1a).

Joint toughness is at the level of conventional brazed joints produced with the brazing alloys and base metals used in the tests discussed. It amounts to 10 J/cm at most. The cross sections of the fractured joints show no plastic deformation while the fracture propagates across the brazing material (Fig. 1a).

3.1. Structure of the new reinforced joint

Ductility of the base metal and the reinforcement at the brazing temperature affects the structure of the new brazed joint with the coalescence of the reinforcement with the base metal.

If the reinforcement is more ductile than the base metal, then the wires get flattened and sinking of the reinforcement into the base metal is negligible. The initial joint width d_j (Fig. 1a) will reduce due to compression during brazing to a width d_b. Consequently, round wires get flat and coalesce with the base metal at a certain width d_c (Fig. 1b). Individual reinforcement wires can coalesce together (width d_1) if pressure on the pieces ensures sufficiently strong transverse deformation of the reinforcement wires (Fig. 1c). Brazing alloy residues are limited to the joint edges among the wires.

If the reinforcement is less ductile than the base metal, the reinforcement will sink into the base metal and coalesce with the base metal at a certain width d_c (Fig. 1d). The base metal will surround the wires across a large area. If compression is strong enough, opposite flows of the base metal can coalesce in the joint centre (width l_2), which additionally reinforces the joint (Fig. 1e). Brazing-alloy residues are limited to the middle of the joint along the wires.

A combination of the two structures, i.e., strong wire flattening and its sinking into the base metal, may occur as well (Fig. 5E).

Regardless of the new reinforced joint structure, the load will be transmitted directly from the base metal to the reinforcement. The joint strength depends on the active-volume fraction of the reinforcement which is defined by the width of coalescence of an individual reinforcement wire with the base metal d_c (Figs. 1b and d). Joint toughness is very good, which is confirmed by strong deformation of the test-piece cross-section (Figs. 1c and e). The joints show 5 to 15 times higher toughness than the conventional brazed joints, i.e., the joints without the reinforcement wires coalesced with the base metal. Fractures will propagate along the line of coalescence, the wires and the base metal (Figs. 1c and e) depending on the material combinations of the base metal and the reinforcement.

Metallurgical reactions among all the components of the reinforced brazed joint are important. The materials have to be selected so that no undesired phenomena occur which could eliminate the effect of reinforcement.

3.2. Metallurgical reactions

The reinforcement can coalesce with the base metal in two ways, i.e., in liquid state, in which case the brazing material takes an active part in bonding, and in solid state, in which case the brazing material takes no part in bonding of the two partners. It is important that coalescence occurs with the solid solution which is strong and tough.

3.2.1. Coalescence of the reinforcement and the base metal in liquid state

With the combinations of the brazing materials and base metals used, two metallurgical phenomena were established, i.e.:

a) formation of the solid solution from the eutectic brazing alloy with the particle precipitation in the base metal and/or the reinforcement or without it;

b) formation of a continuous layer of the brittle inter-metallic phase between the reinforcement and the new solid solution formed in the joint.

In order that the solid solution may start forming from the eutectic at the base metal and the
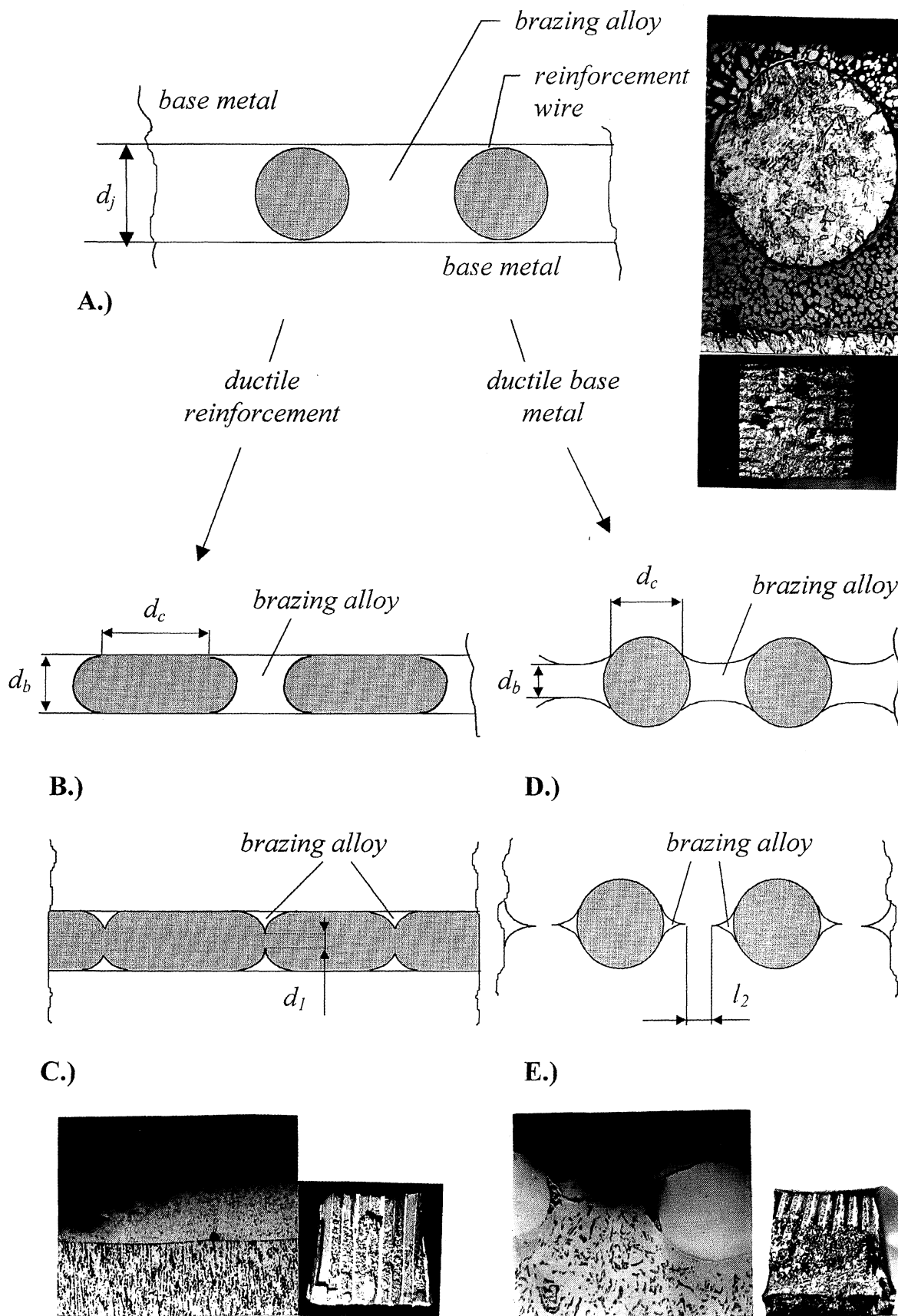
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Figure 1. Different structures of the reinforced brazed joint (macrosections of fractures, x2, structures: A: x 50; C, E: x 25).

Figura 1. Diferentes estructuras de las uniones armadas por soldadura (macro seccionamiento de las roturas, x 2, estructuras: A: x 50; C, E: x 25).

reinforcement, the concentration of an element in the brazing alloy should reduce. The only way is diffusion of this element into the base metal and growth of solid-solution crystals from the base metal towards the centre of the brazing gap.

Formation of the solid solution from the liquid brazing alloy may be explained by means of a hypothetical case of brazing X metal with the eutectic alloy having a composition (A) at a brazing temperature T_s (Fig. 2). Between the liquid brazing alloy having the composition (A) and X metal there is no equilibrium possible. The joint is made of two parts of the solid X metal. Between the two we find the molten eutectic having the composition (A). After a certain time at both sides of the filled-in gap a narrow, solid intermediate layer having a composition (C) will form due to dissolution of X metal in the brazing alloy and of Y element in the solid X metal. Consequently, the concentration of Y element in the liquid reduces from (A) to (B), i.e., to less than (B). Y element in the brazing alloy reaches the value at which already in the course of brazing the brazing-alloy composition shifts to the two-phase zone, L+(X). If the brazing time is not long enough to produce this, the solid solution will form only in cooling when the temperature decreases below the liquidus temperature. Thus the solid solution in the gap increases in volume at the expense of the eutectic. Because of the diffusion of Y element into X metal after a certain brazing time at the brazing temperature T_s the eutectic will disappear from the gap and the gap will be completely filled with the solid solution. The latter will make a strong and tough bond between the two parts.
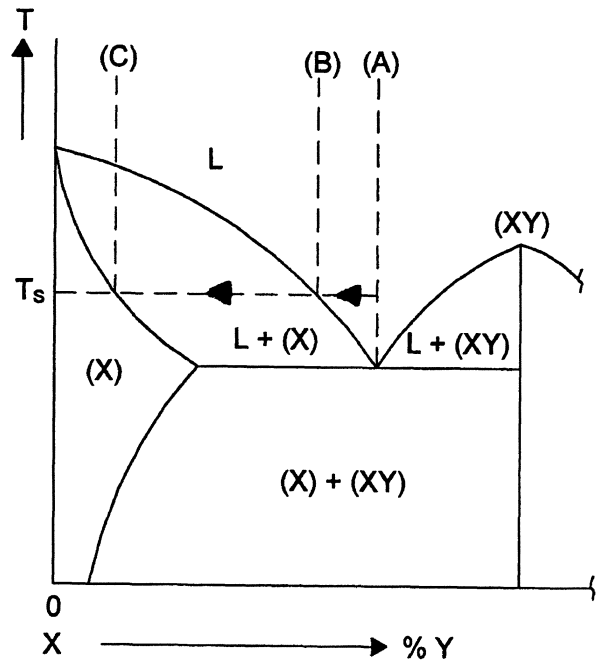

Figure 2. Sequences of solid solution formed by brazing solid base metal with molten eutectic brazing alloy.

Figura 2. Formación de una solución sólida del material base con la aleación eutéctica fundida.

Typical examples are: base metal and reinforcement of austenitic stainless steel, brazing alloy: L-Ni7 (Fig. 3A), brazing alloy L-Ni5 (Fig. 3b) and brazing alloy L-Ni1 (Fig. 3c) and the base metal - copper, reinforcement of copper or copper-clad austenitic stainless steel and brazing alloy L-CuP7 (Figs. 3d and e). The toughness obtained at austenitic steels ranged between 62 and 117 J/cm^2, that obtained at copper between 112 and 150
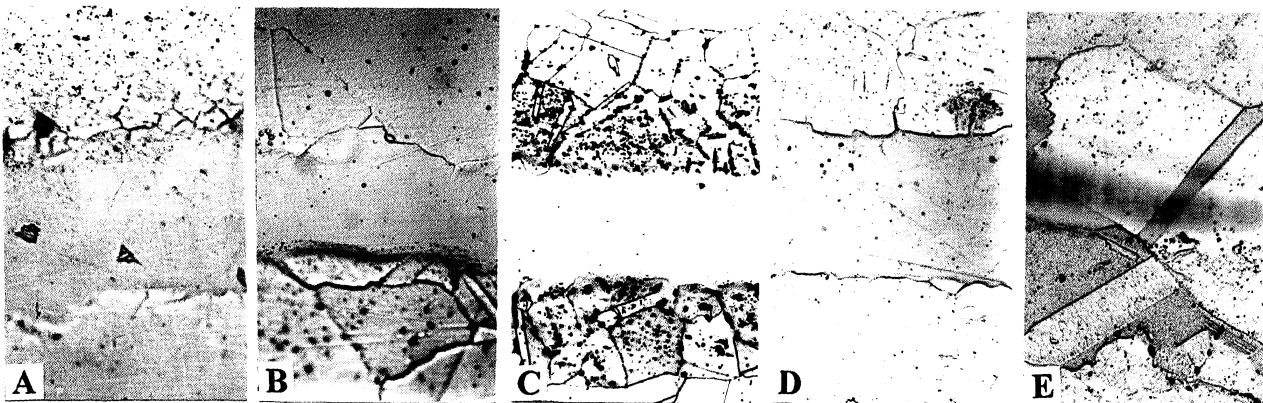

Figure 3. Solid solution at the location where reinforcement wire and base metal coalesced (A, B, C, D: x 320; E: x 400).

Figura 3. Fundición del alambre de la armadura y el material de base con la solución sólida recientemente formada (A, B, C, D: x 320; E: x 400).

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J/cm^2, and when employing copper-clad austenitic stainless steel reinforcement between 30 and 44 J/cm^2.

In all the cases there is the solid solution in the gap between the base metal and the reinforcement wires. This solid solution can get completely homogenized under suitable brazing parameters. It is figure 3e that shows such complete homogenization where a twinning boundary propagates from the joint to the base metal.

In the base metal and the reinforcement of austenitic stainless steel close to the gap, columnar and intergranular precipitates were found with L-Ni1 brazing alloy. The intergranular precipitates were found deeper in the base metal due to more rapid grain boundary diffusion. The neutron-induced autoradiography and the electron microprobe analysis showed complex (Cr, Fe, Ni) borides. Silicon may be found in some precipitates, but generally it was found in the solid solution.

With other Ni brazing alloys precipitation does not occur. Similar findings apply to brazing of copper with the L-CuP7 brazing alloy (Figs. 3d and e). Boron is the only element interstitially dissolving in austenite; therefore, its diffusion to austenite is much faster than those of silicon and phosphorus. Moreover, the inter-metallic phases with the lowest boron contents occur with lower concentrations than in case of phosphides and silicides - Cr_2B: 9.42 wt. % B, Fe_2B: 8.83 wt. % B, Ni_2B: 8.44 wt. % B, Cr_3P: 16.56 wt. % P, Fe_3P: 15.60 wt. % P, Ni_3P: 14.96 wt. % P, Cr_3Si: 15.26 wt. % Si, Fe_3Si: 14.36 wt. % Si, Ni_3Si: 13.76 wt. % Si [10].

Because of fast diffusion of boron to the base metal and the reinforcement, its low solubility in austenite, and formation of borides at much lower concentrations of boron if compared to phosphides and silicides, the base metal and the reinforcement get quickly oversaturated with boron along the brazed gap. This results in strong precipitation of borides at this very location (Fig. 3c).

Because of slow phosphorus and silicon diffusion into the base metal and reinforcement with the L-Ni5 and L-Ni7 brazing alloys, there were no precipitates (Figs. 3a and b). In no case over-saturation with these elements, i.e., achievement of the concentration required for the occurrence of the inter-metallic phases, will occur along the brazed gap. Similar findings apply to brazing of copper and copper-clad stainless austenitic steel with the L-CuP7 brazing alloy. The inter-metallic phase Cu_3P occurs with a content

of phosphorus of ~14.6 % [10], so that no formation and precipitation of this alloy will occur along the gap in solid copper during brazing (Figs. 3d and e).

We have quite a different situation in brazing of austenitic stainless steel with the L-CuP7 brazing alloy. In this case a continuous layer of the inter-metallic phase will form on the reinforcement of austenitic steel (Fig. 4b, 4d - arrows). It can be inferred from Reference[11] that this is a mixed (Fe, Cr, Ni, Cu) phosphide.

Why does the brittle layer of the inter-metallic phase occur in brazing of austenitic stainless steel with the Cu-P type brazing alloy but not with the Ni-P type brazing alloy (Fig. 4a).

Formation of the solid solution at the base metal in the joint from the molten Ni-P type brazing alloy was explained jointly with figure 2. It is essential that the phosphorus content in the molten brazing alloy will decrease through a two-phase liquid-solid solution zone, L+(X). This means that the solid solution in the form of a strip will always form on the base-metal surface in the joint from the molten brazing alloy (Fig. 4a).

An explanation of the formation of the brittle phosphide layer on austenitic stainless steel when a brazing alloy of the Cu-P type is used requires an analysis of ternary diagrams Cu-P-Fe, Cu-P-Cr, and Cu-P-Ni. In the systems there are several kinds of phosphides, but it suffices to deal with the phosphide with the lowest concentration of phosphorus, M_3P. Binary diagrams of metal-phosphorus are all alike. In all cases binary eutectic of the solid solution-phosphide type, $(M)+M_3P$, exists. Binary eutectic concentrations of phosphorus and temperatures T_E are as follows[10]:

(Cu)+Cu_3P: 8.4 wt. % at T_E = 714 °C,
(Ni)+Ni_3P: 11 wt. % at T_E = 880 °C,
(Fe)+Fe_3P: 10.5 wt. % at T_E = 1050 °C,
Cr+Cr_3P: 8 wt. % at T_E = 1370 °C.

The solubility of phosphorus in all metals at ambient temperature is very low, e.g. in Fe only 0.015 wt. %. Also the highest solubility of iron (Fe) in copper (Cu) (at a peritectic temperature of 1096 °C, at peritectic point, 4 wt. %) and chromium (Cr) in copper (Cu) (at an eutectic temperature of 1077 °C, 0.73 wt. %) is very low. The eutectic and peritectic temperatures of the other binary metal systems concerned are much higher than those of the system (Cu)-Cu_3P. This means that all the surfaces and curves in the ternary systems concerned are descending towards
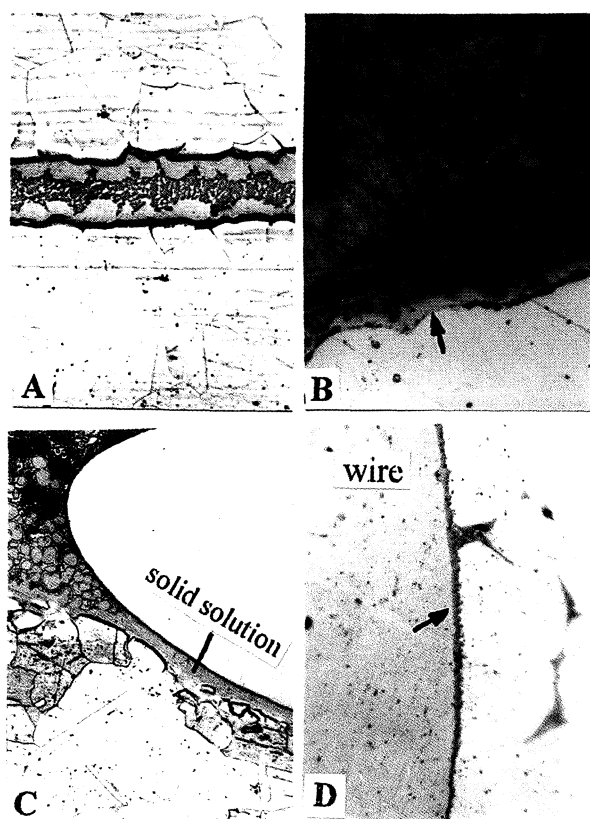
Figure 4. Formation of ductile and brittle layers on base metal in brazed joint (A: x130; B: x 800; C: x 100; D: x 500).

Figura 4. Formación de la capa dúctil y frágil en el material de base en la unión soldada (A: x 130; B: x 800; C: x 100; D: x 500).

the (Cu)-Cu$_3$P system, i.e. towards the copper corner. Because of the low solubility of chromium and iron in copper, the contact points (ternary eutectic point in the (Cr-Cu) - (Cu-Cu$_3$P) - (Cr-Cr$_3$P) system, the liquidus point in the (Fe-Cu) - (Cu-Cu$_3$P) - (Fe-Fe$_3$P) system) shift strongly towards the copper corner.

In brazing of steel at temperatures of 730 °C to 790 °C the L-CuP7 brazing alloy is in the two-phase zone, L+(Cu). In the brazing alloy a certain amount of Fe, Cr and Ni dissolves from the austenitic steel. Thus along the steel in the joint a multi-component molten alloy system forms, from which a complex phosphide layer, primarily on steel, will form (Fig. 4b - arrows). This will happen in the solidification of the brazing alloy or as early as in the course of brazing if the contents of phosphorus, iron, chromium, and nickel achieve the values at which the composition of the brazing alloy will shift from the pure liquid to the liquid-phosphide zone. This is similar to the formation of the solid solution. This is confirmed by a part of the ternary diagram Cu-Fe-P in the copper corner

at temperatures of 700 °C, 900 °C, and 1000 °C [12]. Thus this is not decomposition of a part of Cu$_3$P and a reaction with steel as stated in the literature[11]. We can speak about Cu$_3$P decomposition only in the solid state process. At a brazing temperature, however, Cu$_3$P does not exist in the L-CuP7 brazing alloy because the latter is hypoeutectic. In case of a hypereutectic brazing alloy, it is clear it will be the phosphorus from the liquid phase and not the phosphorus from Cu$_3$P solid phase that will react with the iron, chromium, and nickel.

Figure 4c) shows the coalescence of the reinforcement wire of austenitic steel and copper as a base metal. The wire is slightly impressed into the base metal. The coalescence is accomplished with the new, Cu-based solid solution formed. The coalescence should be strong and tough, however, this is not the case because there is a thin phosphide layer (Fig. 4d - arrow) between the wire of austenitic steel and the new solid solution formed. This is a barrier preventing a mutual tough coalescence of austenite and the copper-based solid solution. This results in a joint toughness of 3.6 J at most.

With this combination of the materials there are two phenomena, i.e., growth of the tough solid solution from copper towards austenitic steel and growth of the phosphide layer from steel towards copper. The rate of growth of the phosphide layer is negligible if compared to that of the solid solution. This indicates that the majority of phosphorus diffuses into copper. The metallurgical compatibility of the base metal, the reinforcement, and the brazing alloy should be such that the mutual coalescence with the solid solution will be accomplished without any intermediate brittle layer of inter-metallic phases.

3.2.2. Coalescence of the reinforcement and the base metal in solid state

A liquid brazing alloy is inert to the reinforcement and the base metal; therefore, it does not take part in the coalescence process between the base metal and the reinforcement. It only fills voids among the reinforcement segments and prevents oxidation in the joint. In our case the brazing alloys L-Ag40Cd and L-Ag44 were used. A close contact being required between the reinforcement and the base metal, it is indispensable that the pressure applied during brazing be sufficiently high. The pressure concerned will allow wire flattening,

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i.e., impression of the wires into the base metal, flow-out of the brazing-alloy from the area of coalescence, diffusion of elements between the reinforcement and the base metal as well as deformation of faying surfaces. Recrystallization and grain growth beyond the faying surface are produced by high temperatures. Thus the reinforcement and the base metal get strongly interconnected without the action of the brazing alloy. The microstructure of the coalesced surfaces differs and depends on the reinforcement material and the base metal used.

Along the line of coalescence of the reinforcement wire of low-carbon steel (0.06 % C) and the base metal of low-carbon steel (0.16 % C) there is a thin pearlite layer (Fig. 5a). This is the strongest and sufficiently ductile zone. A fracture occurs in ferrite in the reinforcement (Fig. 5a and 1c). Toughness of these joints amounts to 106-124 J/cm^2 while that of the non-coalesced reinforcement wire and the base metal amounts to max. 10 J/cm^2.

Figure 5b) shows the line of coalescence of the reinforcement wire of austenitic steel X5 CrNi 18 10 and the base metal of low-carbon steel (0.16 % C). A strong and sufficiently tough intermediate low-carbon martensite layer forms due to the diffusion of carbon, chromium, and nickel between the reinforcement of austenitic steel and the base metal of low-carbon steel. A fracture occurs in the base metal and along the line of coalescence (Fig. 1e). Toughness of these joints amounts to 87-110 J/cm^2 while that of the non-coalesced reinforcement with the base metal amounts to max. 6 J/cm^2.

Figure 5c) shows coalescence of the reinforcement wire of carbon steel (0.7 % C) and the base metal of low-carbon steel (0.16 % C). The small brazing-alloy residues between the wires can be seen in the centre of the figure (arrows). They do not affect the properties of the joint. The line of coalescence is not observable. The joint area shows Widmannstätten pearlite-ferrite microstructure. The majority of pearlite is found in the wire area. Its portion in the base metal reduces gradually with the increasing distance from the joint. This proves that carbon from the reinforcement additionally alloyed the base metal along the joint and hardened the joint area. The toughness of these joints amounts to 76 - 150 J/cm^2 whereas that of the reinforcement non-coalesced with the base metal amounts to max. 10 J/cm^2.

Figure 5d) shows the coalescence of the reinforcement wire of carbon steel (0.7 % C) with the base metal of medium-carbon steel (0.34 % C). The line of coalescence is not visible. In comparison with figure 5c), a high carbon content can be observed in a larger joint area. The microstructure is pearlite with ferrite at the grain boundaries. At the left-hand margin of figure 5d) in the joint area, a zone of oxidized brazing-alloy residue between the wires is visible. The small residues of the inoxidized or oxidized brazing alloy do not affect the properties of the joint. The toughness of these joints amounts to 48-58 J/cm^2 whereas that of the reinforcement non-coalesced with the base metal amounts to max. 7 J/mm^2.

The polished micro specimen in Figures 5e and f) shows the coalescence of the reinforcement wire of austenitic steel X5 CrNi 18 10 and the base metal, i.e., free-machining austenitic stainless steel. The line of coalescence is visible quite well because of the sulphide inclusions in the base metal. Although the inclusions occur also at the line of coalescence itself, the joint is strong and tough because they do not occur in a continuous line. The fracture propagates primarily through the base metal along the line of coalescence (Fig. 5e). A sharp contour of the torn-out base metal at the reinforcement wire can be observed. At the line of coalescence no brazing-alloy residues can be observed (Fig. 5f). The same applies to the joints consisting of the reinforcement wire and the base metal of X5 CrNi 18 10 steel. In this case the line of coalescence, in the polished state, cannot be observed. With both austenitic steels chosen, the joint toughness ranged between 72 and 150 J/cm^2.

4. CONCLUSIONS

The joint is efficiently reinforced if the wire reinforcement and the base metal coalesce directly, i.e., without the intermediary of the brazing alloy. Coalescence may occur by means of the solid solution formed from the molten brazing alloy or in solid state by recrystallization and grain growth beyond the faying surfaces. In solid state, the brazing alloy does not participate in joining. For coalescence of the reinforcement and the base metal across a large area it is necessary to exert pressure on the test specimens. The coalescence at a larger area is achieved by flattening of the wires with a round cross section or their sinking into the base metal. The materials involved should be such that no brittle layers occur. The volume of coalescence may be additionally alloyed by the elements from the reinforcement or the base metal.
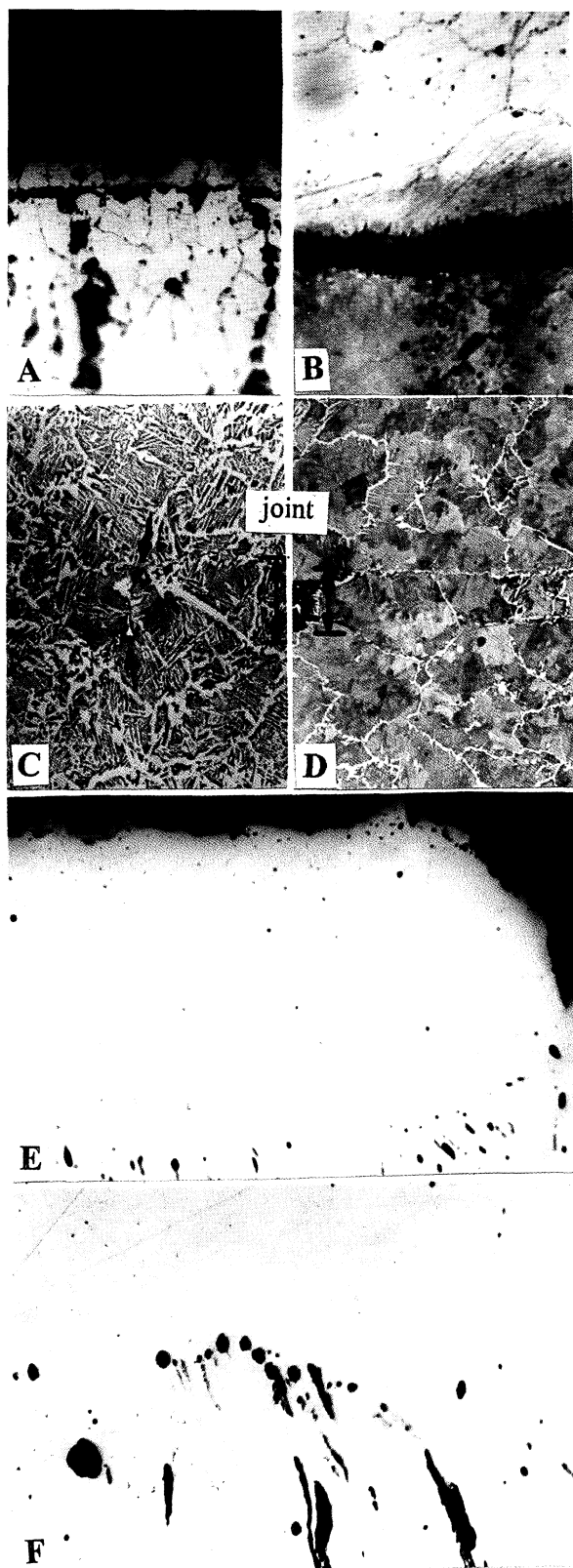
Figure 5. Coalescence of reinforcement and base metal in solid state (brazing alloy L-Ag40Cd - A: x 400; B: x 820; C, D: x 25; brazing alloy L-Ag44 - E: x 80, F: x 400).

Figura 5. Fundición de la armadura y el material de base en estado sólido (metal de aportación para soldeo fuerte: L-Ag40Cd - A: x 400, B: x 820; C, D: x 25; metal de aportación para soldeo fuerte: L-Ag44 - E: x 80, F: x 400).

Very strong and sufficiently ductile, clearly separated intermediate layers hardening the line of fusion may occur. Such a case is low-carbon martensite formed between the reinforcement of austenitic steel and the base metal of low-carbon steel. If in the reinforcement there is an element with a high diffusion rate in the base metal, it will additionally alloy the area of coalescence by a gradual decrease of its concentration from the joint to the base metal. Carbon is such an example. It strengthens the joint zone on steel. High strength and toughness of joints can be obtained also with free-machining sulphur-alloyed austenitic stainless steels, which additionally confirms the versatility of the joining technology applied.

The joint properties are controlled by the reinforcement and not by the brazing alloy. That is to say that the brazing alloy loses its function of a filler material. The properties may match those of the base metal if suitable brazing parameters are used.

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