A New Approach to Improving the Properties of Brazed Joints

Improvement of mechanical properties was achieved by a reinforcement composed of a system of parallel wires

BY B. ZORC AND L. KOSEC

ABSTRACT. Composite brazing filler metals improve mechanical properties of brazed joints. Application of a new, parallel-wire reinforcement, along with an appropriate working procedure, in the brazing of metallic materials offers solutions to several problems related to brazed joints. All reactions between constituents of the brazed joint are noteworthy. Joining of the reinforcement to the base metal without a brazing filler metal at the contact face between the reinforcement and the base metal is required. In this case, the reinforcement has a decisive influence on tensile strength, toughness and resistance to crack propagation in the reinforced brazed joint since the reinforcement is situated in the brazed-joint plane.

Coalescence of the reinforcement with the base metal may be obtained in two ways, *i.e.,* in some cases by diffusion brazing if the combination of the brazing filler metal, the base metal and the reinforcement permits, and in other cases by diffusion welding of the base metal and the reinforcement. In the latter case, the brazing filler metal is inert as far as the reinforcement and the base metal are concerned.

In both cases, application of compressive force is required to permit coalescence of the reinforcement wire with the base metal over a large area.

Introduction

Reinforcing brazed joints with composite brazing filler metals has been known since the 1930s. At that time, the terms “reinforcing” and “composite” in the present meaning were not known since investigations on composite materials started only in the 1960s (Ref. 1).

Development and use of composite brazing filler metals have been closely related to the manufacture of various carbide tools. In brazing on metal shanks, there have frequently been difficulties, *e.g.,* cracking susceptibility of brazed joints or even hard metals, due to the different thermal expansivity of the two components. The problem may be solved in several ways, including the use of a composite brazing filler metal.

From an article of van Houten (Ref. 2), it is learned that the use of brazing filler metals with the addition of carbides was known in the 1930s. The article also gives a detailed description of the use of different metal inserts (meshes, thin plates). It is noticed that all the ways of reinforcing known at that time are still used today.

Flat inserts (Refs. 2–7) of ductile metals, *e.g.*, copper, nickel or metals with low thermal expansitivity such as tungsten and molybdenum, were most often used. Each group of materials reduces residual stresses in the brazed joint in its own way. Thus, formation of cracks can be prevented and tensile and shear strengths of the ceramic/metal joint may be improved.

KEY WORDS

Brazed Joint
Reinforced Brazed Joints
Diffusion Brazing
Diffusion Welding
Mechanical Properties
Tensile Strength
Toughness
Crack Propagation

The flat insert, however, does not reinforce the brazed joint at all, since ultimately two joints are obtained: one between the ceramic and the insert and one between the insert and a metal part.

Typical reinforcing of the joint is attained by adding metal meshes and honeycomb structure to the brazing filler metal (Refs. 2, 3, 8, 9). These are common types of stiff and continuous reinforcements. One type consists of the filler metal and stiff reinforcing elements. The second type of filler metal, however, consists of reinforcing elements added as metal (Refs. 2, 8, 9) and nonmetal particles (Refs. 2, 10–12), among which carbon fibers have become very popular lately (Refs. 10–12).

Composite brazing filler metals in particular were used for brazing in wide joint clearances where the metal powder, which does not melt during the process, was added to the brazing filler metal. Some are referred to as artificially made hypoeutectic alloys in which powder stainless steel or nickel alloys are added to nickel brazing filler metals (Refs. 13–15). Others have a typical composite nature, such as nickel-iron powder in a copper filler metal (Refs. 16, 17).

Mechanical properties of brazed joints of carbides or ceramics to a metal indicate that the composite properties of the filler metal are transferred to the brazed joint. In brazing of carbides to steel with a brass filler metal, the addition of steel fibers resulted in almost a doubling in shear strength compared to conventional brazed joints (Refs. 8, 9). The same author states that the application of a mesh of austenitic stainless steel increased shear strength of the brazed joint made with the brass filler metal by 70% in comparison to a nonreinforced brazed joint. A mesh of low-carbon steel did not improve shear strength of the brazed joints made with the brass filler metal. He also claimed metal fibers reinforced the brazed joint

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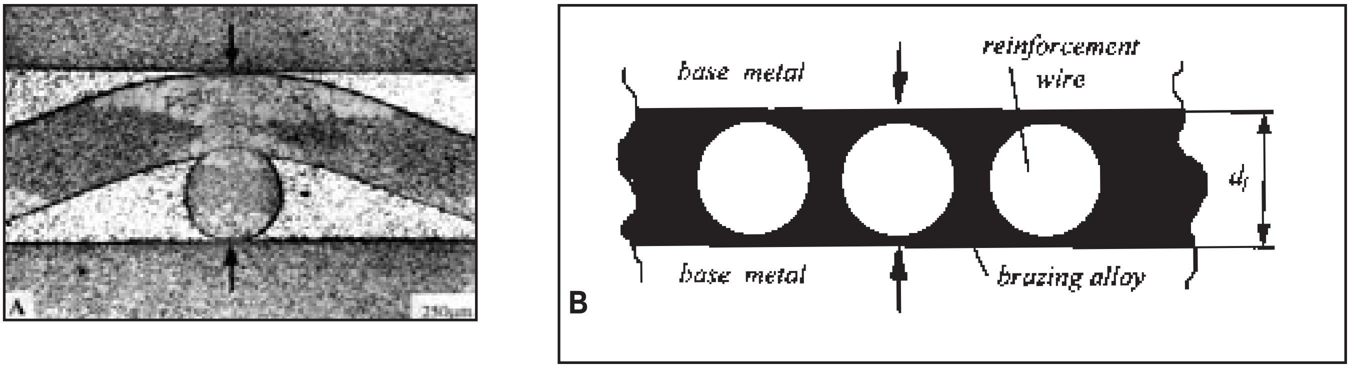

Fig. 1 — State of reinforced brazed joint without coalescence of the reinforcement with the base metal. A — Reinforcement: wire mesh; B — reinforcement: system of parallel wires (d_f, groove of the joint).

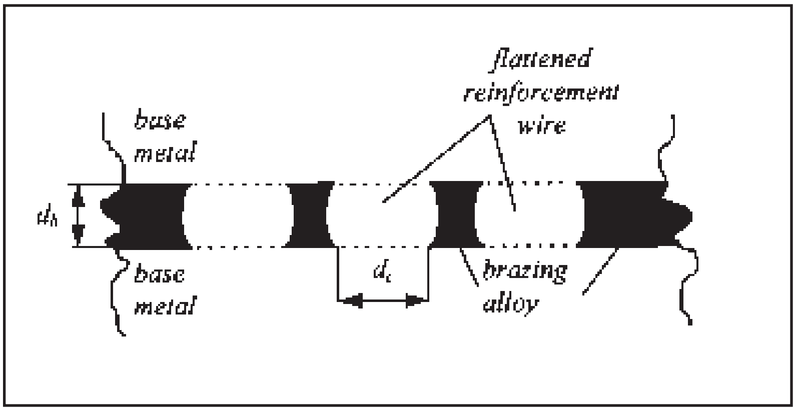

Fig. 2 — State of reinforced joint with coalescence of the reinforcement with the base metal (d_b — groove of the joint; d_c — width of coalescence of the reinforcement wire with the base metal).

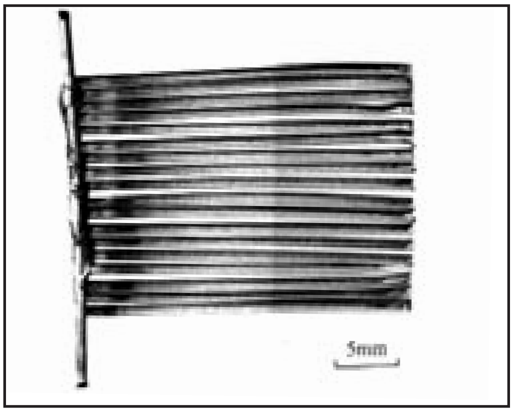

Fig. 3 — Reinforcement (system of parallel wires).

much more strongly than a mesh.

In brazing of alumina and Fe-Ni-Co alloy (Ref. 12), it was found that the addition of approximately 20 vol-% of carbon fibers to a filler metal BAg-8a gave the maximum improvement in shear strength. An addition of bare fibers, however, increased shear strength by 65% and of nickel-clad fibers by 300%.

Similar findings hold true for brazing in wide clearances in metals. For example, Chekunov (Ref. 18) states that the addition of powder, such as molybdenum and tungsten, to the filler metal improves high-temperature properties of brazed joints.

Test results of brazed joints produced with the composite filler metal show typical properties of composite materials, such as influences of reinforcing material, volume fraction of reinforcing elements, surface treatment of reinforcing elements and diffusion reactions between the filler metal and the reinforcing elements. Because the mechanical properties may improve or deteriorate in the production of a composite brazed joint, it is, therefore, indispensable to make a preliminary analysis of all the components selected in order to avoid subsequent undesired effects.

Let us take brazing of austenitic stainless steel with a nickel filler metal in a wide clearance. A considerable improvement of mechanical properties of brazed joints is achieved only if the powder added, which does not melt during brazing, coalesces with a solid solution. If individual powder particles are separated by a lattice of brittle eutectic, improvement is negligible (Ref. 14).

Upon a thorough analysis, a new way of controlling properties of brazed joints is presented. A reinforced brazed joint with drastically improved mechanical properties, in spite of the presence of filler metal, was produced. This improvement was produced by a different arrangement of the filler metal in the brazed joint and the coalescence of the reinforcement with the base metal. The latter may be achieved by a parallel-wire reinforcement, which is a new type of reinforcement in brazing. During brazing, the reinforcement remains in the solid state, *i.e.,* it does not melt.

The new type of reinforcement and its coalescence with the base metal permit a new concept of control and planning of mechanical properties of brazed joints. If there is no coalescence of the reinforcement with the base metal, the reinforcement has no effect on the mechanical properties.

Theoretical Considerations

Generally, conventional brazed joints show low toughness values and poor resistance to crack propagation. This holds true also for tough filler metals such as brass, silver and copper (Refs. 16, 19). Tensile strength of brazed joints can be considerably higher than that of pure filler metal (Refs. 20, 21). This is a result of a narrow clearance, which does not permit the filler metal to deform due to formation of a three-axis stress condition in the brazed joint under an external load.

That is to say that in spite of favorable tensile strength, toughness remains low,

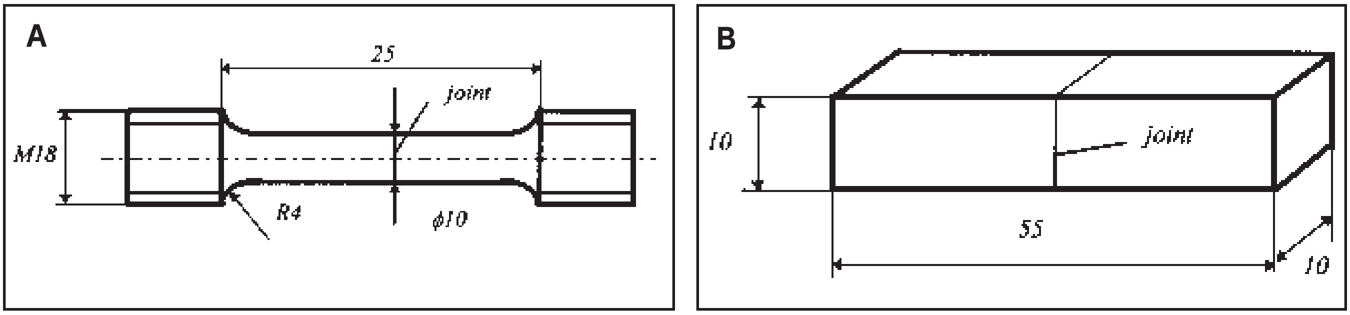

Fig. 4 — Shape and size (in mm) of test specimens. A — For tensile test; B — for toughness test.

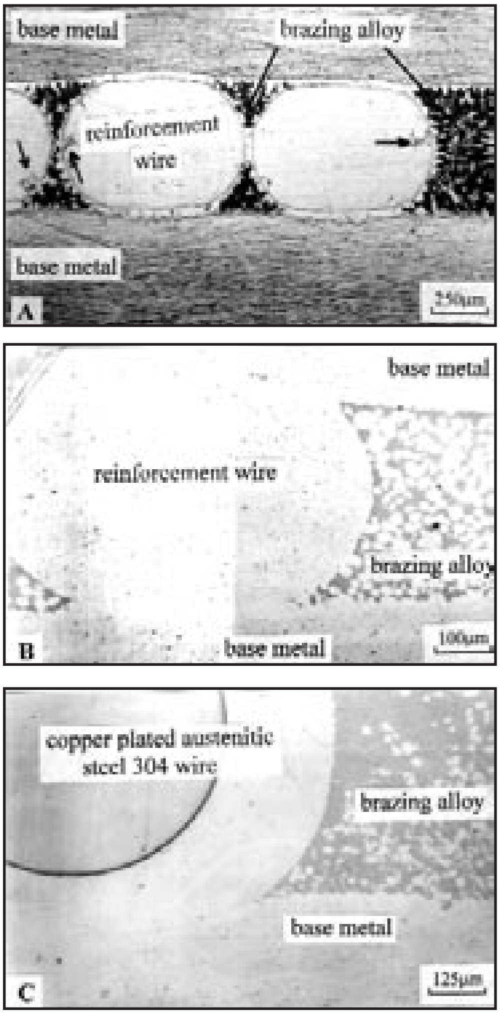

Fig. 5 — Reinforcement/base-metal coalescence obtained by diffusion brazing. A — Reinforcement and base metal: austenitic stainless steel 304, filler metal: BNi-7; B — reinforcement and base metal: copper, filler metal: BCuP-2; C — base metal: copper, reinforcement: copper-plated stainless steel 304, filler metal: BCuP-2.

which limits applicability of brazed joints in comparison to welded joints.

The only efficient method of solving this problem now known is with diffusion brazing, *i.e.,* the TLP® process (Ref. 22), which equalizes the properties of the brazed joint to those of the base metal. The method is limited to a suitable combination of the brazing filler metal and the base metal. Consequently, it is not applicable to brazing of steel with brass or silver filler metals.

Reinforcing of the brazed joint by the parallel-wire method is another new way to eliminate the deficiencies of brazed joints and can bring the mechanical properties of the brazed joint in line with those of the base metal. It was proved that the method was applicable also in brazing steel with a silver filler metal, which indicates its general importance.

Analysis of the Standard Reinforced Brazed Joint

A characteristic of a standard reinforced joint is that there is no coalescence of the reinforcement with the base metal. Its state is shown in Fig. 1.

The figure shows there is a filler metal between the reinforcement and the base metal (arrows). Any reinforced brazed joint is essentially similar to the conventional braze joint in the area between the base metal and the reinforcement (two conventional joints). Consequently, the reinforcement can increase only shear strength of the brazed joint — not tensile strength, toughness and resistance to crack propagation.

This can be explained by the mechanics of composites reinforced by long fibers. The reinforcements shown can be imagined as a condition in a composite among three neighboring fiber planes, among which there is a matrix (filler metal). Because the reinforcement is embedded in the brazed-joint plane, the reinforcement wires have an orientation transverse to the load in a tensile test while the wires never intersect in the direction of load in an impact test. With the tensile load, the condition of equal stresses in all the components of the brazed joint (base metal, reinforcement and filler metal) is fulfilled; therefore, there is no reinforcing of the brazed joint. Tensile strength of the joint depends on the weakest component, *i.e.,* the filler metal or the filler-metal/base-metal interface and filler-metal/reinforcement interface, respectively, which is the same as in a conventional brazed joint. Tensile strength values may be lower than those of conventional joints because in the reinforced joint with a mesh or parallel wires several defects usually occur and there is no narrow-groove effect.

A similar conclusion can be drawn on toughness and crack propagation in the joint. A crack will most certainly take the easiest track, *i.e.,* through the filler metal or along the filler-metal/base-metal interface or the filler-metal/reinforcement interface. The reinforcement has nothing to do with crack arrest regardless of the reinforcement shape. This was proved by the first series of test specimens having the parallel wire reinforcement with which toughness values remained at the level of conventional joints. Tensile strength of the brazed joints reinforced in this way was not tested. It was judged that this was unreasonable due to low toughness values.

Analysis of the New Reinforced Joint

An ideal reinforced brazed joint may be obtained if the wires are embedded perpendicular to the joint plane, *i.e.,* in the direction of tensile load in the tensile test, and coalesce with the base metal. Such an arrangement of the brazed joint being quite difficult, the reinforcement was embedded in the joint plane. The only condition required by the reinforcement for it to actively transmit a load through a joint is its coalescence with the base metal — Fig. 2.

The essential element is, therefore, a sufficiently large area of coalescence of the reinforcement with the base metal. This may be achieved, however, only by applying pressure to test pieces during brazing. An analysis of potential reinforcement shapes showed that the reinforcements known hitherto (meshes, honeycomb structure) are not fit for the purpose. The reasons are that numerous defects form in the apertures (a closed system) and the area of potential coalescence with the base metal was too small. It was found that an ideal reinforcement for such a brazed joint was a system of parallel wires having a round cross section. Such a reinforcement has the following important properties:

1) It offers a chance to control the initial volume fraction (V^0_w) of the reinforcement in the joint from minimum to maximum.

2) The reinforcement geometry permits "intersection" of the conventional joint as many times as there are wires in the reinforcement, and consequently, there are that many barriers.

3) Compression can produce flattening of the round wires and their coalescence with the base metal.

4) The flattened wire permits good flow of the filler metal from the interface.

5) Parallel wires form an open system, which permits flow of excess filler metal, flux residues and gases from the joint along the "channels" between the wires.

Two ways of coalescence of the reinforcement with the base metal were anticipated: diffusion brazing and diffusion welding. Both methods were tested.

It is very important to properly choose the reinforcement material in consideration of the brazing filler metal and the base metal. It is essential to prevent the formation of brittle layers. As far as composites and metallurgical effects are concerned, the most suitable reinforcement is the one made of a material similar to the base metal but having higher tensile strength and high toughness values. In theory and practice this indicates a transfer of a weak point from the joint to the base metal and elimination of the risk of formation of brittle layers.

Testing

To prove the general validity of the hypothesis, tests were performed on different steels and copper. The test produced conventional joints, reinforced joints without any coalescence of the reinforcement with the base metal and reinforced joints with coalescence of the reinforcement with the base metal.

The following combinations of materials were used:

1) base metal: copper; reinforcement: copper, electrolyticly copper-plated austenitic stainless steel 304, austenitic stainless steel 304; brazing filler metal: BCuP-2; rod diameter = 2 mm.

2) base metal: carbon steel, C = 0.16%; reinforcement: mild steel, carbon steel, C = 0.70%, austenitic stainless steel 304; brazing filler metal: 40 wt-% Ag, 19 wt-% Cu, 21 wt-% Zn, 20 wt-% Cd (L-Ag40Cd, DIN 8513), BAg-5, rod diameter = 2 mm.

3) base metal: carbon steel, C = 0.34%; reinforcement: carbon steel, C = 0.70%; brazing filler metal: L-Ag40Cd, BAg-5, rod diameter = 2 mm.

4) base metal: austenitic steel 304; reinforcement: austenitic stainless steel 304; brazing filler metal: L-Ag40Cd, BAg-5, rod diameter = 2 mm, BNi-7 (paste).

In brazing of steels with a silver filler metal, a flux Type 3A was used. The reinforcement was made of parallel wires (Fig. 3) by microplasma welding. The diameters of the wires were 0.6, 0.7 and 0.8 mm, depending on the material used. An initial volume fraction of the reinforcement V^0_w was approximately 0.7 mm. All the joints were made by torch brazing, except in the case of the brazing filler metal BNi-7 (furnace brazing in a shielding atmosphere of decomposed ammonia).

Conventional joints were brazed without controlling the brazing clearance (this depended on the weight of the upper part of the test piece). Tensile test pieces were made of rods with round cross sections (diameter = 22 mm for the lower part, 18 mm for the upper part) and toughness test pieces of rods having a square cross section of 15 mm for the lower part and 12 mm for the upper part. Brazing time was 10–12 s and 5 min (in the furnace), respectively. Brazing temperatures ranged as follows: 760–780°C (BCuP-2), 1040–1050°C (BNi-7) and 620–650°C (L-Ag40Cd).

The same kinds of rods and the same brazing parameters were used to produce the reinforced joints without coalescence of reinforcement with the base metal.

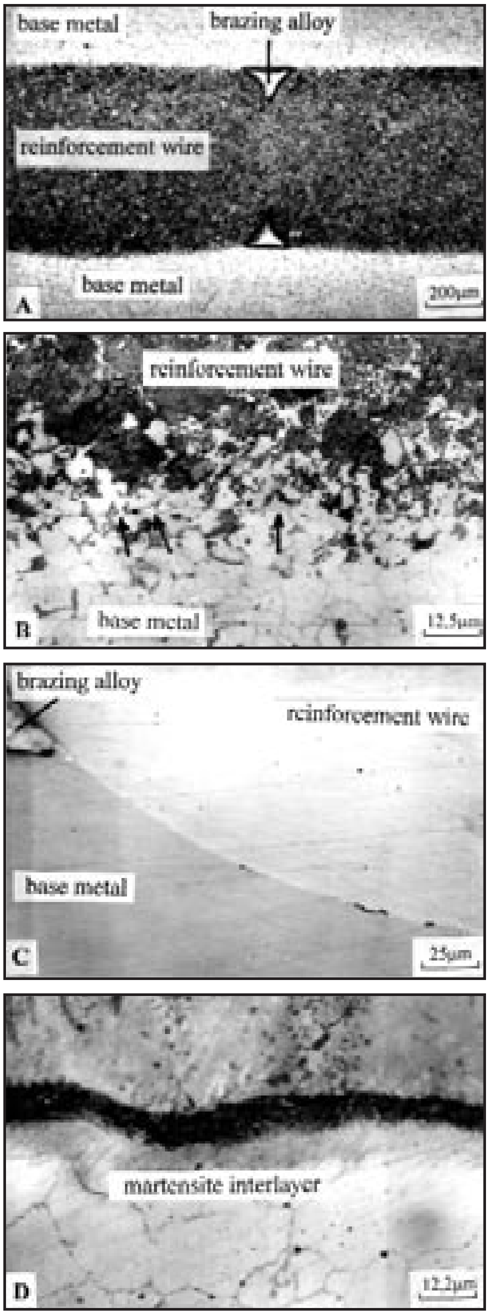

Fig. 6 — Reinforcement/base-metal coalescence obtained by diffusion welding. A — Base metal: steel with 0.16% C, reinforcement: steel with 0.7% C, filler metal: L-Ag40Cd; B — line of wire/base-metal coalescence; base metal: steel with 0.16% C, reinforcement: steel with 0.7% C, filler metal: L-Ag40Cd; C — base metal: steel with 0.16% C, reinforcement: steel 304, filler metal: L-Ag40Cd; D — base metal: steel with 0.16% C, reinforcement: steel 304, filler metal: L-Ag40Cd.

The reinforced joints with coalescence of the reinforcement with the base metal were made of rods with a round cross section (diameter = 25 mm) with application of compression. The filler metal was in a molten state during the total duration of the brazing process (copper with BCuP-2: 30 s at a temperature of 780–800°C, steels with BNi-7: 15 min at a temperature of 1030–1060°C,

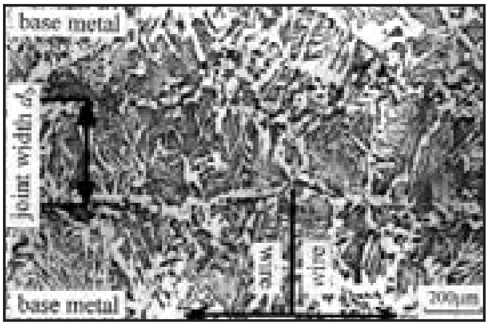

Fig. 7 — Final state of the reinforced joint — diffusion welded joint; base metal: steel with 0.16% C, reinforcement: steel with 0.7% C, filler metal: L-Ag40Cd.

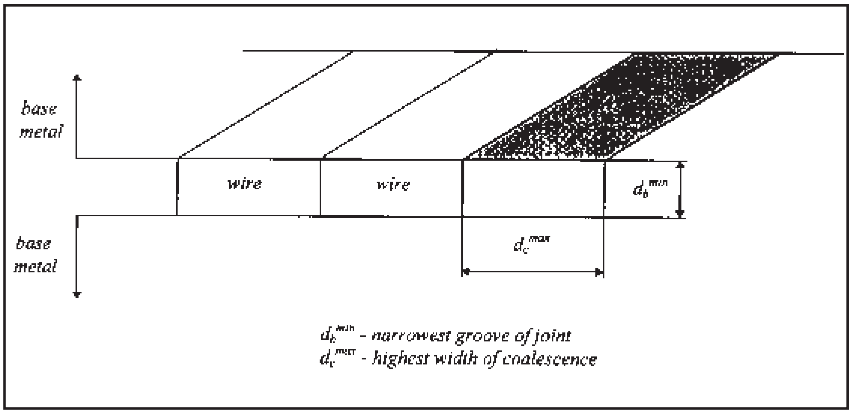

Fig. 8 — Potential final state of the reinforced brazed joint with coalescence of the reinforcement and the base metal.

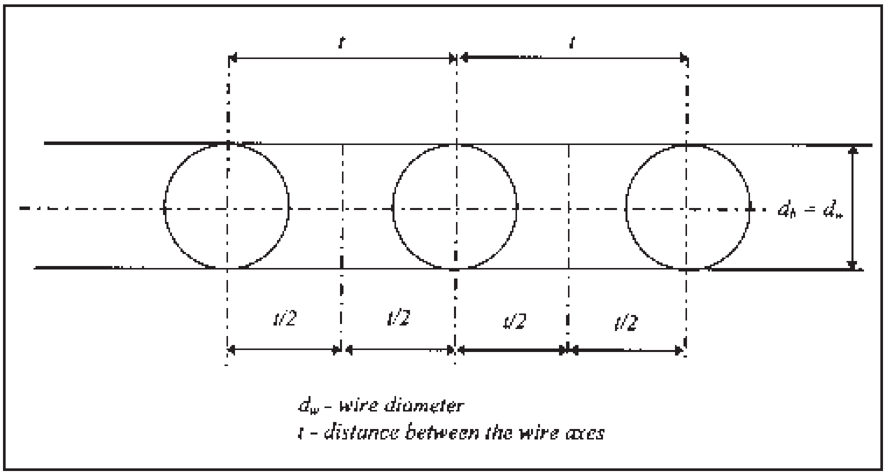

Fig. 9 — Geometrical arrangement of the reinforcement wires in a joint.

steels with L-Ag40Cd or BAg-5: 5 or 15 min at a temperature of 800–850°C). Compression force for copper was 25–30 N/mm^2. For steel the initial compression force was 60–66 N/mm^2, while for the duration of brazing a compression force of 37–43 N/mm^2 was maintained.

A metallographic examination of the joints was made. Tensile strength and toughness of the joints were measured and fractured surfaces were analyzed.

Tensile strength of the joints was measured on a test specimen having a round cross section (Fig. 4A) and toughness on the test specimen without a notch — Fig. 4B. The notch was not applied because some conventional brazed joints disintegrate when a notch is made and in order to be able to make a comparison of our results with those of other authors (Ref. 23). The reinforced joints were impact tested in the direction of the reinforcement wires. In all the cases the hammer energy amounted to 150 J.

Results and Discussion

Mechanical Properties of the Joints

The first series of the test pieces was made with both silver filler metals, but there were no differences to be observed between the two; therefore, the tests were continued with the filler metal L-Ag40Cd. Results of the mechanical tests are given in Table 1.

Test results obtained indicate very low toughness of conventional joints regardless of the base metal and the filler metal (brittle or ductile) used. The same values were obtained with the reinforced joints in the samples where the reinforcement has not coalesced with the base metal — Fig. 10B.

Tensile strengths on joints of steel and copper made with the tested filler metals generally attain lower levels of tensile strength for the normalized condition of steel and the soft condition of copper. In spite of somewhat lower tensile strength for joints of austenitic steel made with the filler metal L-Ag40Cd, experience and literature data indicate that it is possible to produce joints exceeding 500 N/mm^2. Characteristicly, very low tensile strength is attained in joints of austenitic steel made with the filler metal BNi-7.

The addition of reinforcement of suitable material that coalesces with the base metal (for copper a reinforcement made of copper and for steels a reinforcement made of different steels) considerably improves toughness and ductility in spite of filler metal residues in the joint. Some joints remained unbroken after the impact test (toughness > 150 J/cm^2).

The reinforcement essentially affects tensile strength of the joints, which is best observable on steel with 0.34 % C and on austenitic steel.

The test results show that the reinforcement made of a material equal to the base metal is suitable as well. Strength and toughness values comparable to those of the base metal were obtained.

An unsuitable reinforcement material, such as a reinforcement of austenitic steel on copper with a filler metal BCup-2, achieves lower values for mechanical properties than conventional joints. In this case a brittle, continuous phosphide layer is obtained around the wires. The problem may be solved by a suitable cladding, which is indicated by the reinforcement of electroliticly copper-plated austenitic steel.

Generally, a considerable improvement in mechanical properties of the joints may be realized from a suitably selected combination of all materials.

Metallographic Examination

Metallographic examinations confirmed the hypothesis that the reinforcement may coalesce with the base material in two ways:

1) By diffusion brazing, in which a proper combination of all the materials permits the formation of a solid solution, which strongly and toughly interconnects the reinforcement and the base metal (base metal: copper, reinforcement: copper or copper-plated steel, filler metal: BCuP-2; base metal and reinforcement: stainless steel, filler metal: BNi-7);

2) By diffusion welding, in which the filler metal is inert to the base metal and the reinforcement serves only to fill the space between the joint components (base metal and reinforcement: different steels, filler metal: L-Ag40Cd, BAg-5).

In both cases, pressure is required for the reinforcement wires to flatten and coalesce with the base metal over a larger area.

Figures 5 and 6 show coalescence of the reinforcement with the base metal obtained by diffusion brazing and by diffusion welding, respectively.

In the joints in which the coalescence of the filler metal with the base metal is achieved by diffusion welding, small remains of the filler metal may be found at the line of coalescence; however, they do not affect the properties of the joint — Fig. 6B.

Stress cracking may be observed in the tensile zones of the wires due to wire flattening. The filler metal pours into the cracks — Fig. 5A.

It was observed that the reinforcement wires can coalesce if they are close enough to each other, *i.e.,* if the joint is pressed strongly enough to reduce the initial distance among wires in the reinforcement. In this case there is no stress cracking since locations of the highest tensile stresses change in to pressure zones. A negative influence may be exerted only by the formation of larger cracks in the case of an inert filler metal since the filler metal in the crack does not change the structure. With a reactive filler metal, however, the filled-in cracks change from eutectic to a tough solid solution, while the properties of the crack equalize with those of the base metal. With carbon steel and a reinforcement of austenitic steel, a martensite interlayer is formed at the boundary due to the diffusion of elements — Fig. 6D.

Figure 6A shows that compression during brazing may deform the wires so strongly that instead of a brazed joint a diffusion welded joint is obtained. The reinforced brazed joint changed into a diffusion welded joint since there is little filler metal in the joint. Such an extreme case is shown in Fig. 7 where the joint area is filled with the reinforcement alone. The wires have coalesced with each other and with the base metal so that there is practically no filler metal. Such a joint cannot be considered a reinforced brazed joint. It is much easier to treat it as a uniform base metal (steel with 0.16% C) in which there is a narrow layer of material with a higher carbon content (0.16% < C 0.7%) and higher strength.

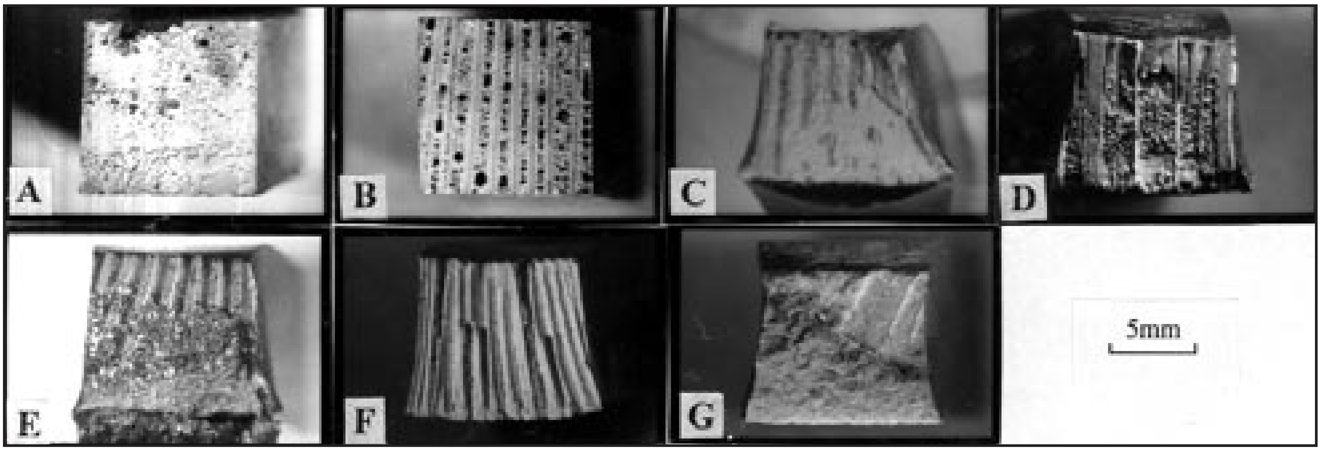

Fig. 10 — Fracture surfaces after impact test. A — Conventional brazed joint on steel (filler metal: L-Ag40Cd); B — reinforced joint on steel without reinforcement/base-metal coalescence (filler metal: L-Ag40Cd); C — good reinforcement/base-metal coalescence (base metal: copper, reinforcement: copper, filler metal: BCuP-2); D — good reinforcement/base-metal coalescence (base metal: steel with 0.16% C, reinforcement: mild steel, filler metal: L-Ag40Cd); E — good reinforcement/base-metal coalescence (base metal: steel with 0.16% C, reinforcement: austenitic steel 304, filler metal: L-Ag40Cd); F — good reinforcement/base-metal coalescence (base metal and reinforcement: austenitic steel 304, filler metal: BNi-7); G — good reinforcement/base-metal coalescence (base metal and reinforcement: austenitic steel 304, filler metal: L-Ag40Cd).

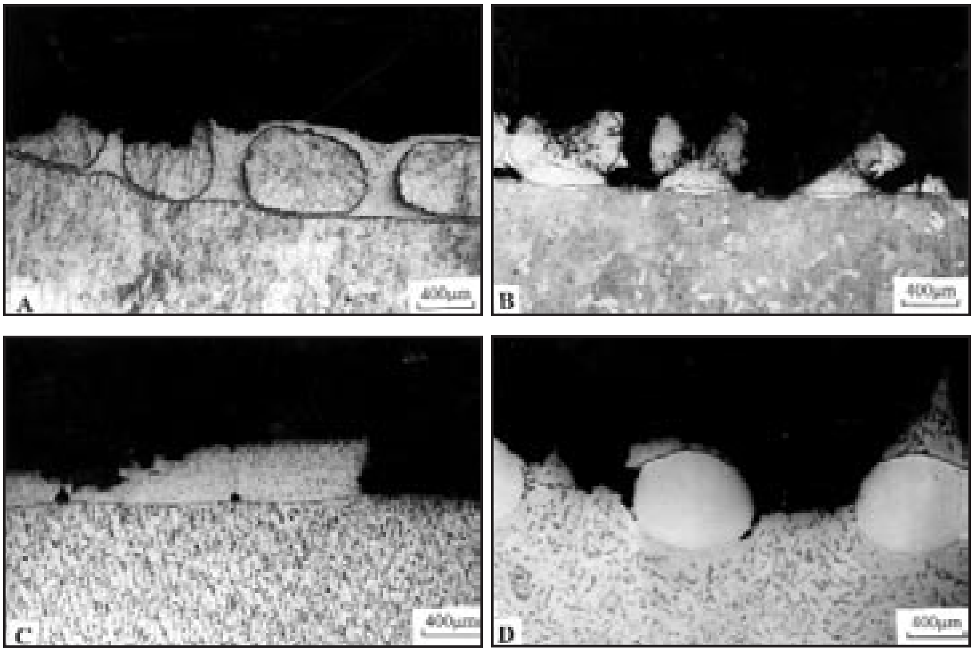

Fig. 11 — Fracture paths in reinforced brazed joints with strong coalescence of the reinforcement with the base metal. A — Base metal and reinforcement: copper, filler metal: BCuP-2; B — base metal and reinforcement: steel 304, filler metal: BNi-7; C — base metal: steel with 0.16% C, reinforcement: mild steel, filler metal: L-Ag40Cd; D — base metal: steel with 0.16% C, reinforcement: steel 304, filler metal: L-Ag40Cd.

Such a joint ensures transfer of a weak point into the base metal.

The active volume fraction (defined by coalescence width of reinforcement wires, d_c — Fig. 2) of the wire may change from $V_{wc} = 0$ into $V_{wc} \approx 1 = V^{\max}_{wc}$. The maximum active volume fraction of the reinforcement $V^{\max}_{wc}$ may be obtained when the wires coalesce with each other in the groove d_b and change into a rectangle — Fig. 8. Then there is no filler metal left in the joint. Because of equal areas of the circle and rectangle, it can be written as follows:

$$P = \frac{\pi d^2}{4} = d_c^{\max} \cdot d_b^{\min} \qquad (1)$$

The greatest width of wire flattening is determined by wire distribution and depends on the distance between the wires' axes — Fig. 9.

Owing to a constant distance between the wire axes, an individual wire can spread during compression to each side for only half the distance between the wire axes (t/2). At that point, the wires touch each other in a line. Each wire can thus spread only for the width equal to the distance between the wire axes (t). With further compression, the wire width does not increase, but the coalescence width of the wires and the base metal and between the wires increases. With the narrowest groove ($d^{\min}_b$), the width of coalescence ($d^{\max}_c$) attains the highest value, which is equal to the distance between wire axes. It can be written as follows:

$$d_c^{\max} = t$$
$$P = d_c^{\max} \cdot d_b^{\min} = t \cdot d_b^{\min}$$
$$d_b^{\min} = \frac{p}{t} = \frac{\pi d^2}{4t} \qquad (2)$$

To attain the maximum active volume fraction compression of the reinforcement (contraction of the joint) depends on the distance between the wire axes in the reinforcement.

Mechanical properties of the reinforced joint depend on its condition, which is clearly shown by fractured surfaces — Fig. 10. The fractured surfaces show poor toughness characteristic of conventional joints and joints without coalescence between the reinforcement and the base metal. The fractured surfaces show no deformations in cross section. The fracture runs through the brazing filler metal. The reinforcement has nothing to do with crack arrest and has no influence on mechanical properties. Porosity may be observed in the joints . The condition shown in Fig. 10A and 10B is characteristic of all the material combinations tested.

The fractured surfaces of the reinforced joints with coalescence between the reinforcement and the base metal are typically tough — Fig. 10 C, D, E, F, G. Strong lateral cross-section expansion is visible. The fracture may run in the joint across the wires or wire/base-metal interface but may also deviate into the base metal — Fig. 10E, 10G, 11D. This proves that the joint is in its optimum condition (optimum brazing parameters used with a particular material combination) comparable to the base metal. Interchanging fields of coalescence of the reinforcement wires and the base metal and of the filler metal are more or less clearly visible (filler metal in Fig. 10C: gray lines, filler metal in Fig. 10 D, G: light lines).

Figure 11 shows cross sections perpendicular to the fractured surfaces. Regardless of fracture propagation, the reinforcement has a decisive influence on the mechanical properties of the joint.

Figure 11D shows another type of joint in which the wires do not flatten significantly, but they are impressed into the the base metal. This phenomenon is due to the fact that at the brazing temperature the base metal is much more ductile than the reinforcement. Consequently, compression produces deformation of the base metal toward the joint center.

Theoretically, a reinforcement layer embedded into the uniform base metal and coalesced with it is attainable. This may also be considered a diffusion welded reinforced joint.

Conclusions

The results confirmed the initial hypothesis that by reinforcing brazed joints with a new type of reinforcement composed of parallel wires, the mechanical properties of brazed joints may be controlled and essentially improved. But coalescence of the reinforcement with the base metal is a prerequisite for such an improvement. The reinforcement material has to be carefully selected, taking into account the base metal as well as the filler metal so that no brittle intermediate layer occurs. This may be achieved by a suitable cladding. The reinforcement and the base metal may coalesce in the braze pool by means of a newly formed solid solution (diffusion brazing), which is possible with some material combinations. Another method is solid-state coalescence (diffusion welding). In this case, the brazing filler metal does not take part in the process; therefore, a considerable compressive load is required. The load produces recrystallization and growth of crystal grains, which, in addition to solid-state diffusion, allow coalescence of the reinforcement with the base metal.

The composite brazed joint with the new stiff and continuous reinforcement composed of parallel wires results in the desired arrangement of microstructure phases in the brazed joint. The filler metal in the joint gets trapped between the individual wires. In spite of the presence of filler metal, the reinforcement strongly affects the mechanical properties of the joint. The influence of the reinforcement is controlled by the width of coalescence of the wires and the base metal. The latter determines the active volume fraction of the reinforcement.

The active volume fraction V_{wc} of the reinforcement does not depend on its initial volume fraction V^0_w. Regardless of the initial volume fraction of the reinforcement in the joint, the active volume fraction amounts to zero if the reinforcement and the base metal have not coalesced. If during compression the reinforcement is deformed, the active volume fraction may change from $V_{wc} = 0$ to $V_{wc} = 1$ when the reinforcement completely fills up the joint zone.

If the reinforcement deforms slightly or not at all but there is a plastic flow of the base metal, the active volume fraction may change from $V_{wc} = 0$ to $V_{wc} = V^0_w$. In this case, the joint is composed of the base metal and the reinforcement alone. That is to say that by optional compression of samples, various states of the reinforced brazed joint are obtained. The brazed joint may finally turn into a diffusion welded joint. A decisive influence on the mechanical properties is exerted by the reinforcement and not by the brazing filler metal.

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