

# Some Developments in Rotating Heat-Exchanger Brazing Technology

Good joints are obtained using 19 Cr-10 Si, 13 Cr-10 P, and 23 Mn-7 Si-5 Cu nickel-base filler metals and by immersing the rotating heat-exchanger matrix in a bath of cement and brazing filler metal

BY IGNAZIO AMATO

## Introduction

The economical limits as regards heat exchangers are governed not only by the costs of the materials but also manufacture and maintenance during the whole service life.

The main general trends in the development of gas turbine heat exchangers are as follows:

1. Increasing the effectiveness. If greater quantities of heat have to be exchanged and the pressure losses reduced, this necessarily means using larger heat exchangers.

2. Reducing the size. There are several ways of reducing the size of the exchangers. One is by decreasing the equivalent diameter of the elements forming the exchanger matrix. Reducing the size reduces the material required to an equivalent extent. This means that (a) the length of elements can be curtailed and (b) the thickness of the material can be very often decreased as well. Reducing in the amount of material required is a very important point where expensive materials are necessary for coping with high fluid temperature. However, reducing the size of the exchanger in this way complicates manufacture, with the final results of lower material but higher manufacturing costs.

Perhaps the best way of meeting these contrasting requirements is to use rotating (better named regenerative) heat exchanger where the fluid agent is replaced by a solid matrix of interconnected elements which are al-

ternately heated by the initially hotter fluid and cooled by initially cooler fluid. The elements used in these regenerative matrices are parallel plates with corrugated plates between, brazed together.

The size, shape and arrangement of the elements determine the volume of the interstices compared with the volume of the whole matrix that is the volumetric permeability of the matrix. Regenerative matrices built up from these elements can be brought into contact with the two heat exchanging fluids in different ways; the best way is obtained through the changeover from the heating to the cooling period of the matrix due to the rotary movement of the matrix; the switchover periods are proportional to initial areas on the heating and the cooling sides of the matrix; in this type of the heat exchanger the fluid agent is replaced by the heat charging and discharging matrix.

A sample of the regenerative matrix utilized in our brazing experiments is shown in Fig. 1.

## Copper Brazing

By far the largest part of all brazing is done with copper or copper-bearing, brazing alloys.<sup>1, 2</sup> This is one reason to initiate the present program using copper as the filler metal. According to the Fe-Cu diagram,<sup>3</sup> in the practical brazing-temperature range for pure copper (1100-1150° C), about 3 to 4% iron is dissolved in the molten copper, and the solid iron, in the same temperature range, can dissolve 7 to 8% copper. Since the mutual solubility of the two metals—Fe and Cu—is comparatively low, small amounts of the filler metal will diffuse through the base metal-filler metal interface into the solid base metal and, in the opposite direction, some-

what larger amounts of the base metal will diffuse into the molten filler metal.

After a certain time, a very thin layer of the base metal adjacent to the base metal-filler metal interface will be saturated with the filler metal. Simultaneously, on the opposite side of this interface, the filler metal will be saturated with the base metal. In conclusion, through these theoretical considerations one may postulate that the base metal-filler metal interface must remain as a sharp dividing plane between the two metals.

In addition since the saturation of the filler metal with base metal occurs rapidly and does not interfere with the subsequent *migration* of the filler metal into the base metal, the rate at which the latter occurs could be determined by measuring the decrease in thickness of the joint with time. But, the term migration is used as the general term which includes all the processes by which filler metal (in this case copper saturated with steel at the brazing temperature) proceeds into the base metal. This includes diffusion either lattice or grain boundary, without regard to whether the filler metal is molten or solid. This also includes liquid metal grain-boundary penetration, which is considered to fall outside the definition of diffusion.

Examination of literature on the diffusion of copper in the steel<sup>4</sup> shows quite evidently that the amounts of copper which diffuse into the crystal lattice of iron, even during a brazing cycle of several hours, are quite negligible. For instance, in order to achieve a decrease of the thickness of the copper joint equal to 0.00008 in., a brazing cycle of 29 hr at 1100° C would be required. A decrease of the joint thickness equal to 0.0008 in. would require a 4-month long brazing

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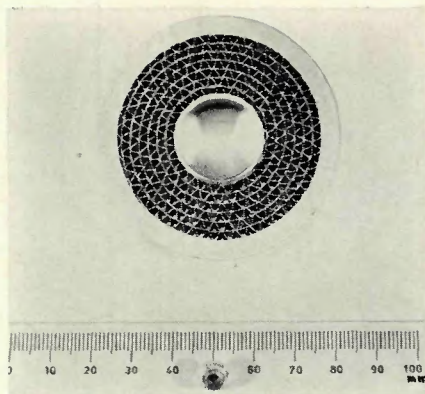


Fig. 1—Sample of rotating heat-exchanger

cycle.

On the other hand, it is known<sup>5</sup> that, in induction brazing of steel bars with pure copper in which case the copper remains in the molten state only for about 1 to 2 min, large amounts of copper penetrate into the grain boundaries of steel, decreasing the joint thickness by at least 0.005 in. Consequently, it can be concluded that, by using induction heating for brazing of steel with pure copper, the amounts of copper which penetrate into the austenitic grain boundaries are at least 5000 times larger than the amounts of copper which diffuse directly into the crystal lattice of the steel. As soon as the liquid copper penetrates into the austenitic grain boundaries, every grain of austenitic close enough to steel-copper interface will be surrounded by a thin film of liquid copper. Due to penetration of the liquid copper in the austenitic grain boundaries, the total area of copper-steel interfaces will increase greatly. The total copper-steel contact area will be at least several times larger than in a joint without any grain-boundary penetration. Diffusion of copper atoms from the given grain boundary into the crystal lattice of austenite grain will start immediately upon the appearance of liquid copper in the grain boundary. Thus, the grain boundary penetration, in turn, in-

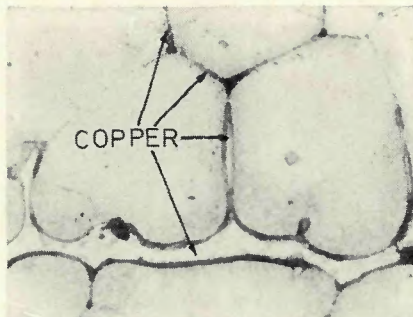


Fig. 2—Micrographic aspect of a copper-stainless steel brazed joint with intergranular diffusion of the copper. Oxalic acid etch.  $\times 750$  (reduced 50% on reproduction)

creases the crystal-lattice diffusion.

A true estimate of the total amount of copper which diffuses into austenitic crystal lattice in one unit of time must include the copper which diffuses through the original copper-steel interface plus the copper which diffuses from the austenitic grain boundaries into the crystal lattice of the austenite. This is dependent upon the depth of grain-boundary penetration which is, in turn, dependent upon temperature, austenite grain size, heating rate, chemical composition of steel, stress distribution in the steel and a large number of other factors.

Therefore, an exact computation of the amounts of copper which will diffuse into the grain boundaries and the amounts of copper which will diffuse into the crystal lattice of the steel must be evaluated through an experimental program.

The first approach, performed at FIAT in order to copper braze the regenerative heat exchangers shown in Fig. 1, was to braze an electrolytic copper-plated (25 microns thickness) stainless steel face sheet to a corrugated stainless steel heat accumulator. For heat transfer reasons, the thickness of the sheet was maintained in the 0.07–0.1 mm range. The brazing process was carried out using a resistance furnace and operating in a hydrogen atmosphere (dew point, about



Fig. 3—Micrographic aspect of the stainless steel erosion by copper during brazing. Oxalic acid etch.  $\times 150$  (reduced 50% on reproduction)

–70° C) at 1120° C for 1 hr. This soaking time was necessary for the copper filler metal to fill the joint area by means of capillary action.

The brazements obtained are tight, but the micrographic examinations showed, in according to the above summarized considerations, an intergranular diffusion of the copper through the stainless steel grains (Fig. 2). This, in some cases, carried to a complete erosion of the stainless steel grains into the copper pool (Fig. 3).

The conclusions derived from these observations mean that there would be difficulty in utilizing rotating heat exchangers produced in this manner at the design operating condition of 500° C. In order to minimize this erosion, a process has been developed which makes use of a dispersion of a cement and filler metal. With this process the assembled rotating heat exchangers are wetted in a dispersion of the filler metal and Nicrobraz cement, a binder for various powdered filler metals. The cement holds the filler powder in place even after it has completely volatilized (between 250 and 350° C) without contamination of the dry atmosphere within the furnace.

Through this process the brazing powder is concentrated for capillary action only on the contact area between the corrugated and face sheets,

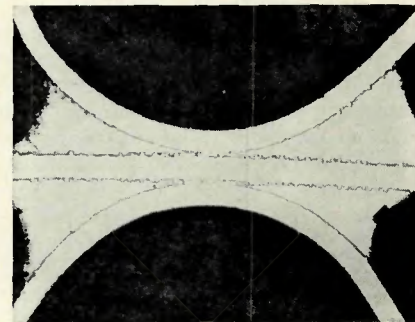
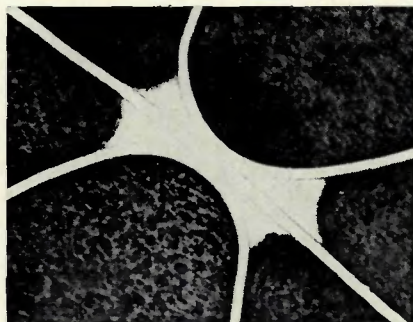
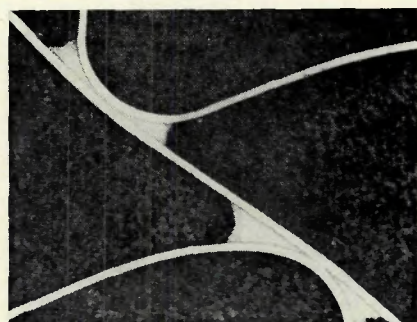


Fig. 4—Micrographic aspect of brazed joints obtained through the immersion process. Filler metal: copper, unetched. A (left)— $\times 40$ ; B (center)— $\times 40$ ; C (right)— $\times 80$  (reduced 48% on reproduction)

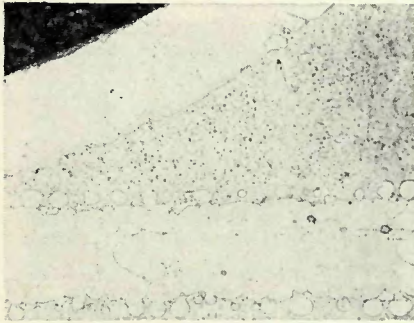


Fig. 5—Micrographic aspect of brazed joints obtained through the immersion process. Filler metal: copper, oxalic acid etched.  $\times 300$  (reduced 50% on reproduction)

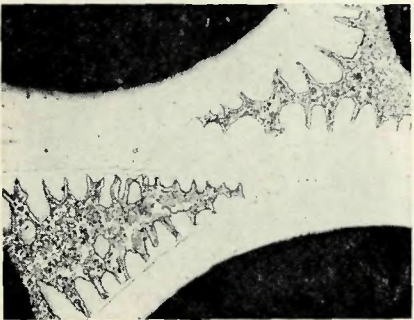
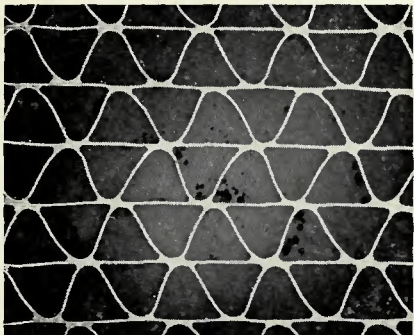


Fig. 6—Micrographic aspect of brazed joints obtained through the immersion process. Filler metal: 19 Cr-10 Si nickel-base alloy, oxalic acid etched. A (top)  $\times 8$ ; B (center)  $\times 150$ ; C (bottom)  $\times 300$  (A reduced 54%, B and C reduced 50% on reproduction)

and also fills any eventual small gaps between the two sheets. The quantity of brazing powder at the brazed joint, depends on the amount of powder contained in the dispersion, which in any case must be optimized for each

application.

Since the brazing filler powder is already at the joint area, short soaking times ( $1/4$ – $1/2$  hr) at the brazing temperature (optimum  $1120^\circ\text{C}$ ) are enough to give good results. In this case, the solution and the erosion originated by the filler metal is not severe. Figures 4 and 5 show some typical joints obtained through this process where the poor copper intergranular diffusion can be seen.

### Brazing with Nickel Base Filler Metal

In selecting an alloy for brazing rotating heat-exchangers, two of most important properties of the alloy to be considered, are strength and oxidation resistance. It is understood, of course, that the alloy should also possess the characteristics desirable of any brazing material, such as a good wettability, ability to flow, ductility, relatively low cost, etc. The life expectancy of the brazed parts should be considered as well as strength requirements, corrosion resistance and the tendency of the brazing filler metal to alloy excessively with the base metal.

Copper and copper alloys, used as brazing filler metal have good strength at moderately elevated temperature, but oxidation resistance is usually satisfactory no higher than about  $500^\circ\text{C}$ . For service temperature of the rotating heat-exchangers exceeding about  $500^\circ\text{C}$  the nickel-base brazing alloys <sup>6-9</sup> should be considered.

The characteristics of nickel make it a good starting point in developing brazing alloys to withstand high service temperatures. It is itself quite ductile and, with proper additions of other elements, has excellent strength and oxidation resistance as well as corrosion resistance at elevated temperatures. Nickel melts above  $1455^\circ\text{C}$ , which makes it necessary to add elements that will lower the melting point. The elements commonly used as alloying additions for brazing alloys are chromium, silicon, boron, phosphorus and carbon. The primary function of chromium is to increase the oxidation resistance and strength, whereas the other elements lower the melting temperature.

The nickel-phosphorus eutectic, consisting of 10–12% phosphorus balance nickel, has been successfully used for service temperatures as high as perhaps  $700^\circ\text{C}$ . The phosphorus not only lowers the melting temperature of nickel to about  $900^\circ\text{C}$ , but also acts as a deoxidizer. This alloy also has relatively low cost making it attractive for application involving large quantities of brazing materials; it has found its principal use to date in large

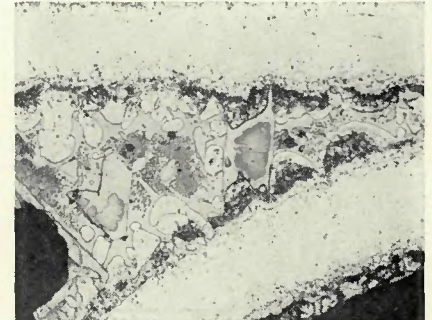
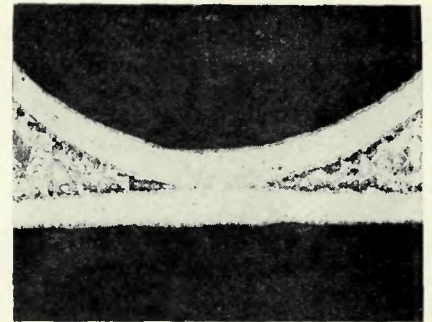


Fig. 7—Micrographic aspect of brazed joints obtained through the immersion process. Filler metal: 13 Cr-10 P nickel-base alloy, oxalic acid etched. A (top)  $\times 150$ ; B (bottom)  $\times 300$  (reduced 50% on reproduction)

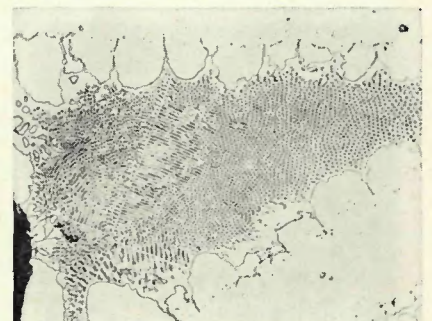
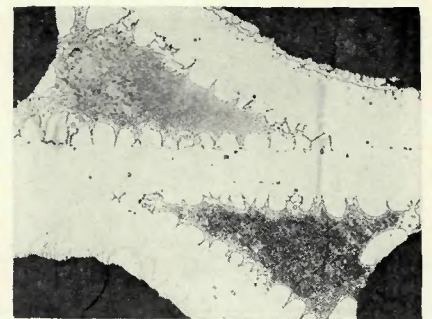


Fig. 8—Micrographic aspect of brazed joints obtained through the immersion process. Filler metal: 23 Mn-7 Si-5 Cu nickel-base alloy. A (top)  $\times 150$ ; B (bottom)  $\times 300$  (reduced 50% on reproduction)

heat exchangers, assemblies previously brazed with copper which limited the service temperature to about  $500^\circ\text{C}$ . A similar brazing filler metal alloy, containing also chromium in order to

improve the oxidation resistance, is supplied with the composition of 13% chromium, 10% phosphorus, balance nickel (AWS A 5.8, B Ni-7).\*

Other high nickel brazing filler metals have been obtained by adding both silicon and boron to nickel in order to reduce the brazing temperature. Its liquidus temperature, depending upon the composition varies from about 1000 to 1150° C they presumably can be used for service temperatures somewhat higher than the nickel-phosphorus composition. Nickel-base brazing filler metals containing silicon and boron are supplied with the compositions of 19% chromium, 10% silicon and balance nickel (conforming to AWS A5.8-BNi-5), and with 23% manganese, 7% silicon, 5% copper, balance nickel (AWS A5.8-BNi-7).\*

For our brazing experiments on the rotating heat exchangers, the three above alloys have been used as brazing filler metals. The process utilized to hold the brazing filler metals at the joint area is the same described in the copper brazing experiments. The brazing cycle has been carried out in a hydrogen atmosphere (dew point -70° C) at 1180° C for 19 Cr-10 Si alloy, at 1010° C for the 13 Cr-10

P alloy and at 1080° C for the 23-7 Si-5 Cu alloy. A soaking time of 1/4 hr at the brazing temperature is sufficient to have solution and solid state diffusion between the brazing filler metal and the base metal.

Figures 6-8 show the micrographic aspect of the brazed joint obtained with the three brazing filler metals. In every case, interalloying particularly at grain boundaries of the base metal has taken place between base metal and brazing filler metal. The extent to which this interalloying is occurred depends upon the brazing filler metal involved. The nickel brazing filler metals used contain elements that promote rapid interalloying, which can be detrimental in thin members of the heat exchanger matrix as elements such as boron, silicon and phosphorus, are consumed by alloying with the base metal; the melting temperature of the brazing alloy increases and a joint that cannot be remelted without going to a higher temperature than the original brazing temperature is obtained. The detrimental effect of the rapid interalloying can give a brazed heat exchanger matrix with cracks or holes. In our experiments it has been noted that the most rapid interalloying is obtained with the 13 Cr-10 P filler metal, which give the worse results by the point of view of the matrix integrity. On the other hand, the results obtained with the 23 Mn-7 Si-5 Cu and 19 Cr-10 Si alloys were such to recommend the use of these brazing filler metals for the heat-exchanger matrix production.

## Conclusions

The following main conclusions can be drawn from the work:

1. It is possible to avoid the detrimental effect of the brazing alloy intergranular penetration through the use of a process which deposits the brazing alloy at the joint area by the immersion of the rotating heat-exchanger matrix in a bath of the cement and brazing alloy.

2. Through the immersion process, the brazing alloy is concentrated for the greatest quantity at the joint area.

3. Good joints have been obtained using copper as brazing filler metal.

4. Good joints have been obtained using as brazing filler metal the 19 Cr-10 Si, 13 Cr-10 P, and 23 Mn-7 Si-5 Cu nickel-base alloys; the 13 Cr-10 P alloy has shown excessive interalloying.

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\* Supplied by Wall Colmonoy Corp., Detroit, Mich., U.S.A., as follows (with nominal compositions shown in parentheses): Nicrobraz 50 (13 Cr-10 P or AWS A5.8-BNi-7), Nicrobraz 30 (19 Cr-10 Si or AWS A5.8-BNi-5), and Nicrobraz 65 (23 Mn-7 Si-5 Cu).

## "Transition-Temperature Data for Five Structural Steels"

By J. H. Gross

Because of difficulties in establishing appropriate criteria for evaluating transition-temperature curves for steels of different strength and thickness, a study was initiated to investigate various energy-absorption, lateral-expansion, and fracture-appearance criteria for five steels having yield strengths in the range 40 to 140 ksi (tensile strengths of 60 to 150 ksi) and for thicknesses corresponding to quarter-, half-, single-, and double-width Charpy V-notch impact-test specimens. The transition-temperature curves for the five steels (ABS-C, A302-B, HY-80, A517-F, and HY-130) are summarized in this bulletin.

The results indicate that of the various criteria for evaluating the Charpy V-notch impact-test performance of structural steels, lateral expansion is the best criterion for compensating for the important effects of steel strength and plate thickness. Moreover, its validity is supported by fracture-mechanics concepts.

Conclusions of the study were discussed in detail in the WELDING JOURNAL, 48 (10), Research Suppl. 441-s to 453-s (1969).

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