Brazing of Stainless Steel Heat Exchangers for Gas Turbine Applications

Brazing procedures for different joint geometries were optimized by varying the form in which the BNi-7 brazing filler metal was applied

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ABSTRACT. Heat exchange is one of the basic problems encountered in the design of gas turbines for automotive applications. Different geometries and materials can be chosen for the realization of suitable heat exchangers depending on the desired efficiency, reliability, fabricability and cost.

Two types of heat exchangers were successfully brazed using different techniques. Depending on the geometry of the heat exchangers, different brazing procedures were adopted as well as brazing parameters. In the case of rotating heat exchangers, the immersion process, that is, dipping of the assembly into a slurry of cement and brazing alloy, was the most appropriate. On the contrary, in the case of cross flow and tubular recuperators, brazing alloy was applied both as a paste and as a tape.

Tests were performed to determine if also in tape form the brazing alloy still had satisfactory wettability.

All the brazing trials performed to optimize the process parameters both for the rotating heat exchangers and the recuperators (joint geometry, application techniques, brazing cycle) are described and the results are given.

After brazing, various tests were performed to qualify the brazed assemblies in view of the specific operating conditions of the heat exchangers.

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Introduction

Heat exchange is one of the basic problems encountered in the design of gas turbine for automotive applications. To be competitive with the diesel engine, a regenerative gas turbine is necessary (Ref. 1). The specific fuel consumption of the simple cycle gas turbine can be substantially reduced by utilizing heat from the exhaust gas to preheat the compressed air. For vehicular gas turbines the heat exchanger is an essential component of the power plant.

There are two main types of heat exchangers currently being used for vehicular gas turbine applications. One is the fixed boundary recuperator, which is often referred to as a conventional direct transfer heat exchanger. In this recuperator, the compressor discharge air and the turbine exhaust gas exchange thermal energy directly through, and are separated by, the heat transfer surface itself.

The second type is a periodic flow regenerator in which the heat is alternately absorbed and rejected by a solid matrix which rotates through fixed fluid streams and is exposed periodically to the high temperature gas and low temperature air.

One of the possible advantages of the rotary unit is the use of more compact surfaces than the fixed boundary type, to give a reduced heat exchanger volume for a given effectiveness and pressure drop. The regenerative matrix is made of parallel plates with corrugated plates between, joined together. The regenerator is used for fairly low pressure ratio cycles.

The two types of recuperator surface geometries most commonly used are plate-fin and tubular construction. In general, the plate-fin type has a smaller volume but is heavier than the tubular unit. To date, the tubular unit is used for lightweight application and for high pressure gas turbine plant.

Referring to the above considerations, an experimental program was carried out to develop the techniques of brazing stainless steel regenerators and tubular recuperators for vehicular gas turbines.

Materials

Base Metals

The ferritic stainless steel AISI 430 for regenerators and the austenitic stainless steel AISI 304L for recuperators were selected. In the regenerative matrix, 0.05 mm thick plates and corrugated plates with a 1 mm pitch and a 2 mm amplitude were employed. Tubes with a 3 mm outer diameter and a 0.1 mm thickness were used for the tubular structure.

Brazing Filler Metal

In selecting an alloy for brazing regenerators and recuperators, two properties have to be considered as the most important: strength and oxidation resistance. It is understood, of course, that the alloy should also possess the characteristics desired of any brazing material, such as a good wettability, ability to flow, ductility, relatively low cost, etc.

Copper and copper alloys, used as brazing filler metal, have good strength at moderately elevated temperature, but oxidation resistance is usually satisfactory at temperatures not higher than about 500 C.

Nickel base materials provide a wide variety of nickel base brazing alloys (Refs. 2-4) to meet, as the service temperature of these heat exchangers exceeds 500 C, the requirements of mechanical properties and heat and corrosion resistance. Many nickel base brazing filler metals contain elements that promote rapid interalloying at grain boundaries of the base metal (Ref. 5). A rapid interalloying can be detrimental to the thin plates of the regenerative matrix and to the thin wall section of the tubular structure. The detrimental effect of this rapid interalloying can give a brazed structure with cracks or porosities.

In a previous work (Ref. 6) it has been noted that an acceptable interalloying can be obtained with the brazing alloy having a composition of 13% chromium, 10% phosphorus, balance nickel (AWS A 5.8, BNi-7). This alloy also has been successfully used for service temperatures as high as 700 C and has relatively low cost, making it attractive for applications involving large quantities of brazing material. For the above considerations, the AWS A 5.8, BNi-7 brazing alloy was used in this work.

Experimental Procedure

A vacuum brazing furnace with maximum operating temperature of 1300 C and ultimate pressure better than 1 × 10^{-4} torr was used.

Regenerators

Brazing tests were carried out using the rotating heat exchanger specimens shown in Fig. 1. A process of putting in place the brazing alloy, which makes use of a dispersion of a cement and filler metal, was developed. With this process, the assembled rotating heat exchanger is wetted in a dispersion of the filler metal and a proprietary cement that is used as 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). Through this process the brazing powder is concentrated for capillary action only at the contact area between the corrugated and face sheets, and it also fills any eventual small gaps between the two sheets. The quantity of brazing powder at the brazed joints depends on the amount of powder contained in the dispersion.

Several brazing tests were carried out to optimize the brazing procedure, that is, the amount of powder contained in the dispersion, the brazing temperature and the soaking time at the brazing temperature, as well as the temperature rate increase, to assure uniform heating and to avoid harmful distortions (Ref. 7). Typical joints obtained through this process with the optimal operating parameters are shown in Fig. 2.

Figures 3-4 show the macrographic and micrographic aspects of brazed joints in preliminary brazing tests with unacceptable operating parameters. The effects of an excessive soaking time at the brazing temperature (Fig. 3) and of a too viscous brazing suspension (Fig. 4) are shown. In the first case, a too long soaking time originates erosion of base metal by filler metal that cannot be acceptable from the point of view of the matrix integrity.

In the second case, operating with a too viscous suspension, the brazing slurry, in the dipping phase, does not flow into the joint area uniformly. After brazing, a few contact surfaces between the corrugated and face sheets were not brazed or brazed only partly.

Integrity and soundness of the brazed joints were achieved, with the aid of micrographic examination,

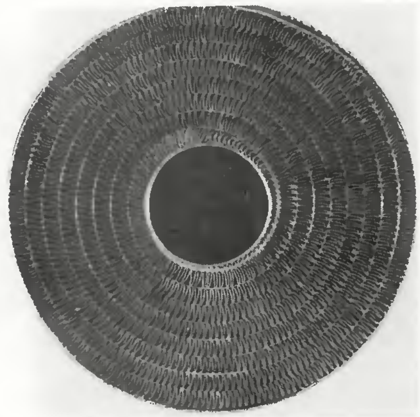

Fig. 1 — Specimen of rotating heat exchanger used in brazing tests

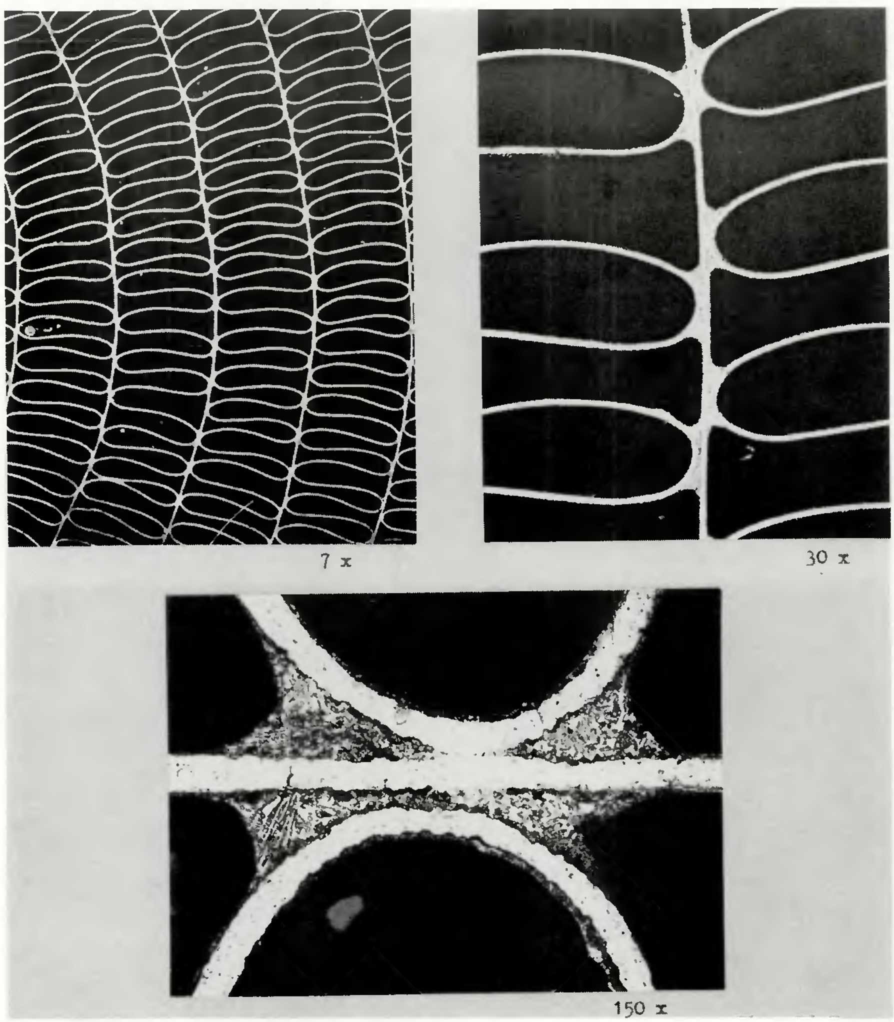

Fig. 2 — Macrographic and micrographic aspect of brazed joints with optimal brazing parameters

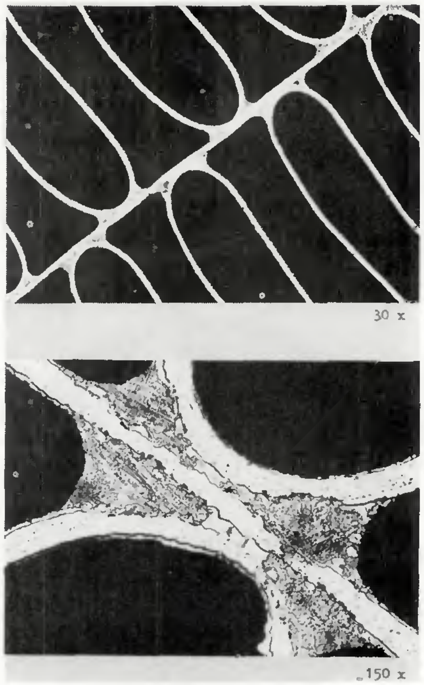

Fig. 3 — Macrographic and micrographic aspect of brazed joints with unsatisfactory brazing parameters: excessive soaking time at the brazing temperature

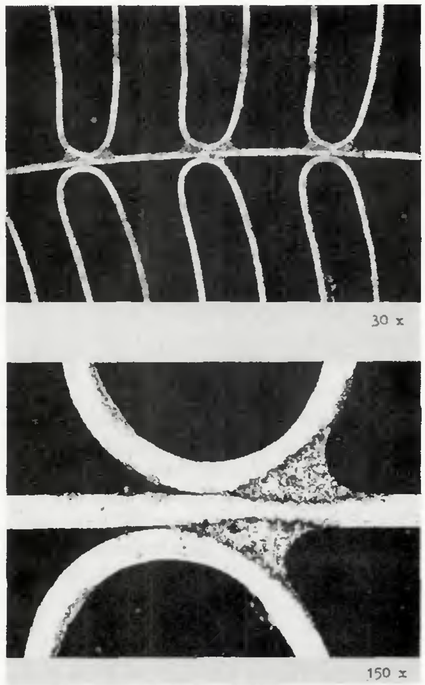

Fig. 4 — Macrographic and micrographic aspect of brazing joints with unsatisfactory brazing parameters: excessive viscosity of brazing slurry

after exposure to the operating temperature (600 C). Microstructure and interdiffusion with bare metal resulted in a uniform as-brazed condition.

To verify reliability of the brazing procedure on larger assemblies, six regenerators with a 230 mm outer diameter were manufactured and brazed employing the optimized brazing parameters (Fig. 5). After brazing, all rotating heat exchangers were tested for leakage and stressed at loads larger than those encountered in operation to evaluate the joint strength.

Recuperators

Tubular recuperator specimens, consisting of 60 thin wall tubes and three 2.5 mm thick tube plates (Fig. 6) have been used for preliminary brazing tests. The assembly geometry and the necessity of assuring brazing of all joints in all tube plates did not allow use of the spraying or immersion techniques to apply the brazing filler metal: these techniques are commonly used on tubular heat exchangers with only two headers (Ref. 8).

A new technique, which makes use of brazing alloy both as a paste and as a tape, has been developed. As to the transfer tape, the material to be applied is supplied in a tape form containing a controlled quantity of brazing filler metal and of binder to hold it in place during the furnace cycle. One side of the transfer tape is a pressure sensitive adhesive.

The tube plates holes were chamfered on one side and machined to provide an appropriate

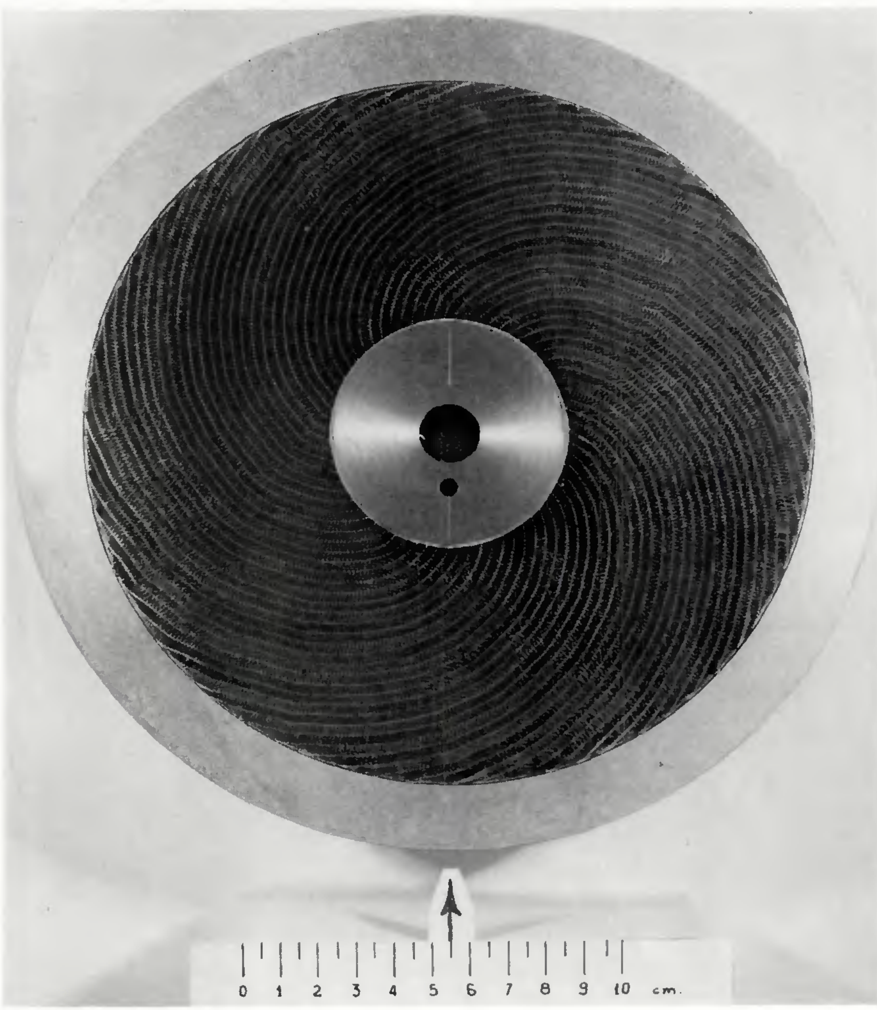

Fig. 5 — Brazed rotating heat exchanger with a 230 mm outer diameter

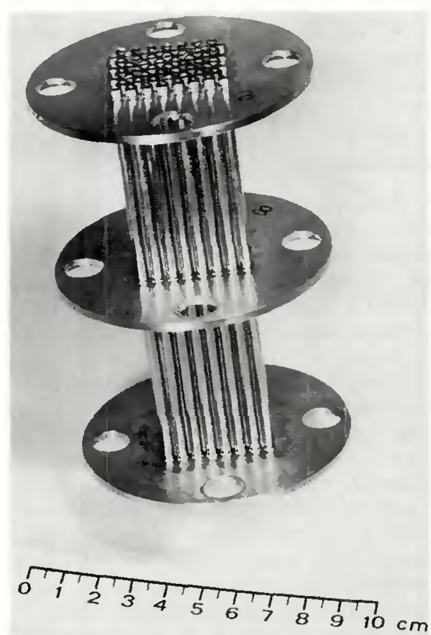

Fig. 6 — Tubular recuperator specimen brazed in preliminary brazing tests

metal-to-metal gap for the brazing filler metal.

Three layers of 0.05 mm thick transfer tape were applied on each tube plate on the tube plate side where the holes were chamfered.

With a stainless steel holding fixture designed to lock the tube in place and to avoid harmful distortions of the assembly during the heat treatment cycle, the tubes were assembled with the tube plates piercing the layers of transfer tape at the holes areas. Between a tube line and the following one, a brazing paste bead of carefully controlled size was applied to supply the correct amount of filler metal required for each joint.

Through this process, at the brazing alloy melting temperature, the filler metal from the transfer tape flows into the joint favoring regular flow into the same joint as the filler metal from the paste bead. The brazing paste bead alone did not assure successful brazing of all joints as the very compact tubular structure makes it difficult to apply the correct amount of filler metal well around each single tube.

Brazing tests were carried out to define the above precedure and to optimize the required amount of filler metal, the brazing temperature and the soaking time at the brazing temperature. Integrity and soundness of the brazed joints were controlled through pressure tightness tests and micrographic examination.

Micrographic examination of the typical joint obtained with the optimized brazing parameters is shown in Fig. 7.

Reliability of this brazing technique has been verified on larger recuperators consisting of 233 thin wall (0.1 mm) tubes of 450 mm length and four 2 mm thick tube plates. Recuperators were brazed (Fig. 8), and then pressure and thermal fatigue tested.

Testing and Experimental Results

Regenerators

Brazed regenerators were tested by static torsional test, twisting stress test and pressure tightness test.

The static torsional test was conducted as shown in Fig. 9. The force, with a lever of 500 mm from the regenerator axis, was applied through an oil control jack driven by a Keelavite unit and controlled by a load cell. The force was applied by steps at levels of 25, 50, 75 and 100% of the maximum prescribed torsional moment (20 kg-m) both in load and in unload phase with return to zero. At each torsional moment level, the related value of deformation was mea-

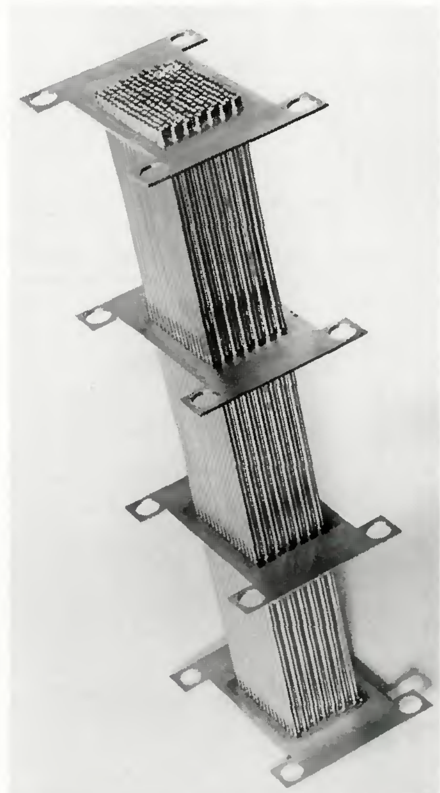

Fig. 8 — Full scale tubular recuperator after brazing

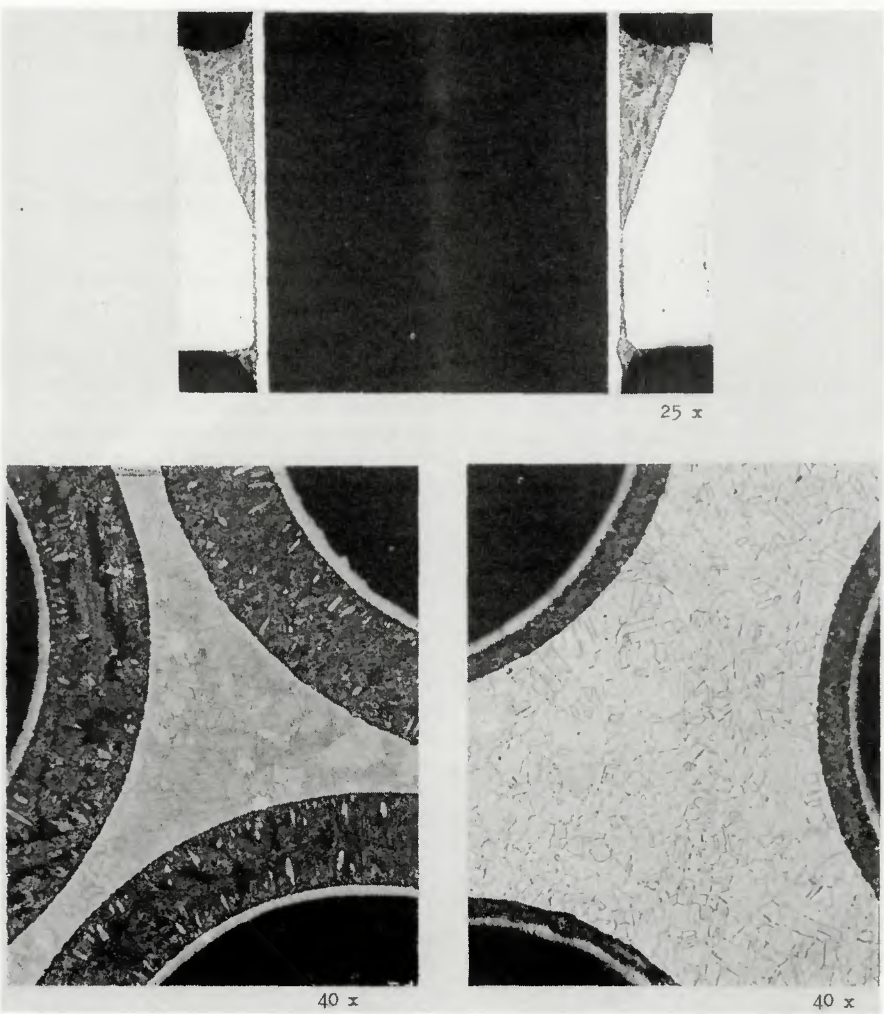

Fig. 7 — Micrographic examination of brazed joints with optimal brazing parameters

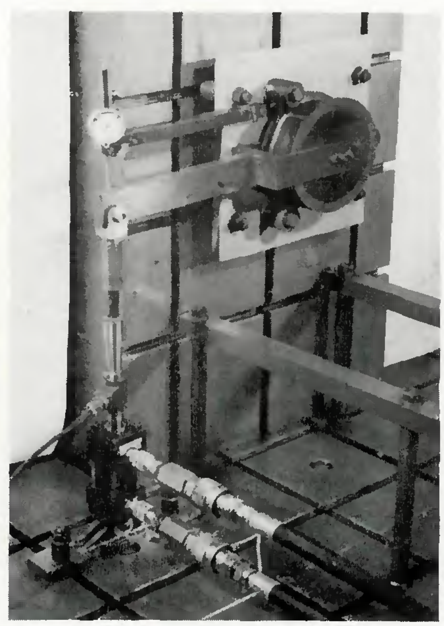

Fig. 9 — Equipment for static torsional test and twisting stress test on brazed rotating heat exchangers

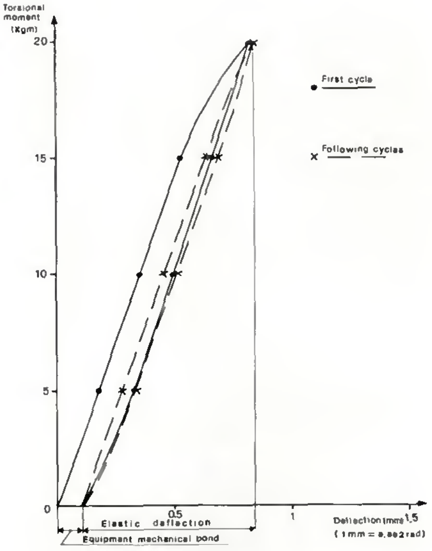

Fig. 10 — Static torsional test: typical load diagram of the brazed rotating heat exchangers

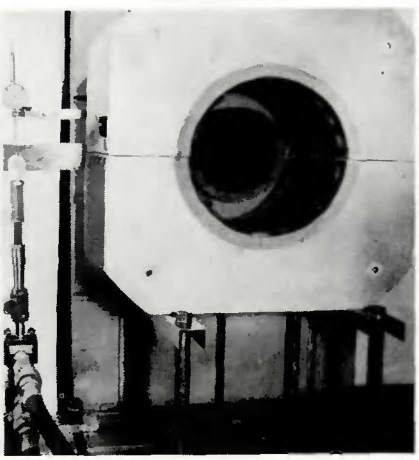

Fig. 11 — Equipment for hot tests on brazed rotating heat exchangers

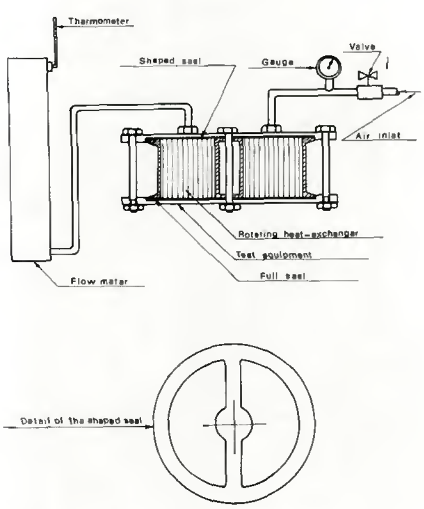

Fig. 12 — Sketch of the equipment for pressure tightness test on brazed rotating heat exchangers

sured by a mechanical operated dial gauge placed on the load axis. The test was carried out before and after the twisting stress test.

Figure 10 shows the outline of the typical load diagram of the brazed regenerators. Regenerators work in the elastic field with a small hysteresis. The permanent deformation in the diagram of the first load cycle is a consequence of the equipment mechanical bond. The repetition of the static test after the fatigue test did

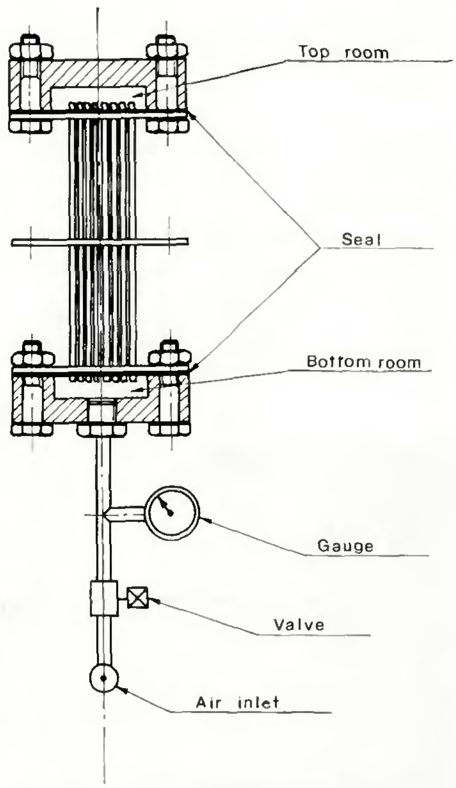

Fig. 13 — Sketch of equipment for pressure tightness test on brazed recuperators

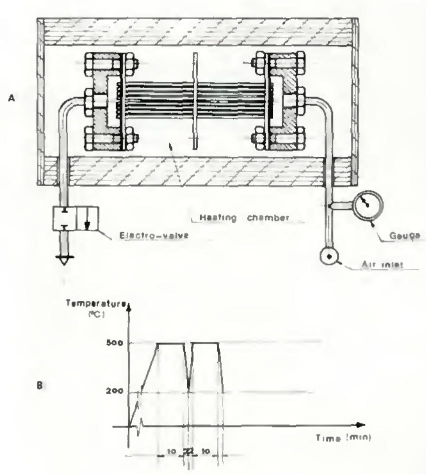

Fig. 14 — (A) Sketch of equipment for thermal fatigue test on brazed recuperators. (B) Thermal cycle adopted for thermal fatigue tests

not show any significant difference of torsional stiffness.

The twisting stress test consists in the execution of 10^6 cycles with pulsating torsional moment from zero to 20 kg-m both at room temperature and at high temperature. The same equipment used for the static torsional test was employed. The twisting stress test was successfully carried out with no yieldings or failures in the brazed joints areas.

The hot test was carried out placing the regenerator into an electric resistance furnace (Fig. 11). Temperatures of 650 C on a regenerator face and of 500 C on the other one were reached, to simulate service conditions.

The pressure tightness test was conducted before and after the torsional test to control the integrity of the brazed joints. Test equipment is sketched in Fig. 12. A Fischer-Porter flow meter with sensitivity of about 0.10 g/sec at the operating conditions was used as leak detector. The leakage test was repeated for six positions of the regenerator with an angular displacement of 30 deg between positions. Each time one-half of the regenerator was pressurized to 3 atm with air at room temperature, so that, for each position, a longitudinal section of the regenerative matrix was stressed. No leaks were detected in these tests.

Recuperators

Brazed recuperators were tested by the pressure tightness test and thermal fatigue test.

The pressure tightness test was carried out before and after the thermal fatigue test by the equipment sketched in Fig. 13. The integrity of the brazed joints was tested by pressurizing to 5 atm with air at room temperature. To simulate the startup and shutdown conditions of the engine and the resulting thermal stresses in the brazed joints, a thermal fatigue testing procedure was developed (Fig. 14a). The test consists of 1000 thermal cycles like that given in Fig. 14b. During the temperature increase from 200 to 500 C and the soaking at this temperature, the recuperator is pressurized to 5 atm. No leakages in pressure tightness tests and no failures of brazed joints in thermal fatigue tests were observed.

Conclusions

The following main conclusions can be drawn from this work:

1. Good joints have been obtained using as brazing filler metal the 13 Cr-10 P nickel base alloy.

2. It is possible to avoid the detrimental effect of the brazing alloy intergranular penetration, by applying

the brazing filler metal through an immersion process in the case of the rotating heat exchangers and through a transfer tape and paste in the case of the tubular recuperators, thus reducing the soaking time at the brazing temperature.

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

4. Through the transfer tape the brazing alloy fluidity is improved.

5. The brazed heat exchangers did perform successfully in the stress and temperature operating conditions.

6. The brazing techniques developed have assured products with high strength and reliability.

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