Titanium Structural Brazing

Second in a series of three papers describes the development of operational procedures for brazing Ti-6Al-4V laminated airframe panels

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ABSTRACT. The titanium laminate brazing process discussed in this paper was part of an integrated program (Ref. 1) to develop designs, evaluate materials, fabricate and test a full scale airframe primary component. A discussion of the early history of the program and the development of a suitable brazing filler metal for the titanium structure are treated in a paper by Kaarlela and Margolis (Ref. 2). Following the brazing procedures described here, a subsequent paper by McHenry and Key (Ref. 3) evaluates the fail-safe strength characteristics of the structure. (Both related papers are published in this issue — ed.)

Process development for joining the beta annealed Ti-6Al-4V laminate made use of the previously developed brazing filler metal, Ag-5Al-0.5Mn. Fabrication methods for retort brazing wide area (4 × 10 ft) beta laminated assemblies were investigated. Primary areas of investigation included tooling development, surface preparation, layup of details, brazing parameters and environmental control. Test results indicated that brazed laminates of satisfactory quality could be achieved by close control of tooling and manufacturing variables.

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Introduction

This paper discusses the development of operational procedures for brazing beta annealed Ti-6Al-4V plate laminates up to 4 × 10 ft in size. The work was part of a broad program (Ref. 1) ultimately aimed at developing a reliable and cost-competitive manufacturing process for a specific brazed structural component, a 5 ft wide by 13 ft long tensile panel.

The historical background of the fail-safe concept as applied to these structures and the development of a suitable brazing filler metal are discussed elsewhere in this issue (see Ref. 2). As described in the paper immediately following (Ref. 3) the brazed titanium laminate constitutes a fail-safe structure since cracks in one lamina do not propagate catastrophically across the braze line.

Operations described here involve tooling, surface preparation, filler metal preparation, layup and brazing procedures. Significant problem areas that were encountered and effectively eliminated are discussed.

Development Evolution

Previous experience with brazed titanium honeycomb panels demonstrated the necessity for strict adherence to details such as cleaning, close tolerances, atmosphere control and proper thermal cycle to attain an adequate braze joint. These considerations became basic throughout process development.

An adequate braze joint was initially described as a joint with 15,000 psi minimum lap shear strength and resistance to stress corrosion attack at a sustained stress of 12,000 psi for 1000 h.

The development program began with small specimens, 0.250/0.250 × 3 × 3 in. in size. Specimen area was increased incrementally to 4 × 5 in., to 8 × 10 in., to 15 × 24 in. sizes. Specimens were tested nondestructively and destructively, and the results were correlated.

Process Development

In developing the operational procedures for brazing titanium laminates, the previously developed Ag-5Al-0.5Mn brazing filler metal was used together with large component specimens. A number of conditions observed in earlier work required further consideration or investigation.

For example, the amount of gap in the joint that will fill with braze filler metal was studied by machining and polishing 0.005, 0.010 and 0.020 in. deep × 1 in. wide faired grooves in one interface surface of a ¼ × 15 × 24 in. plate. After brazing, radiographic and microsection inspection, it was determined the braze filler metal filled the 0.005 in. groove, 60% of the 0.010 in. groove and only 10% of the 0.020 in. groove.

Pressure resulting from varying vacuum on retorts during brazing (from 5 to 25 in. Hg) had no effect on braze quality. Pressures from 20 in. Hg and over shortened the number of times the retort was usable. The ease of elevated temperature forming of titanium plate was an asset in maintaining contact between lamina and helped to produce a brazed assembly to desired dimensional contour. The possibility of entrapping small amounts of contaminants at the filler metal/titanium interfaces dictated the holding of the titanium plate lamina in contact with the braze filler metal throughout the layup and thermal cycle. Braze assemblies were clamped into contact and held by tack welding stainless steel foil strips over the edges.

The time between cleaning and brazing was varied from a few hours to 8 days. While good results were achieved with all specimens a 3 day maximum was preferred.

Thickness mismatch between machined details in the same layer can cause gaps that may not close from creep forming. Remaining gaps of 0.005 in. will fill with braze filler metal if wetting is achieved. Larger gaps exhibit variable amounts of filling.

Since our previous experience was based on brazing titanium sheet material, the surface condition of the machined plates constituted a problem not previously encountered. Steps at the milling cutter overlap area constituted a variable surface condition and braze void resulted in these areas. Belt sanding a minimum of 0.030 in. material from the milled surfaces removed both steps and cutter overlap material. Surface finish to 250 rms had no effect on soundness of the braze joint.

The effective brazing temperature, heating rate and total time above the braze filler metal solidus temperature became the dominant problem areas and are discussed at length below.

Braze Tooling

Tool design and selection of tooling materials is critical when used for brazing titanium alloys. It is mandatory that tooling materials be weldable, relatively free of carbon, and have good dimensional stability at elevated temperature.

Retort Construction

A typical braze retort with associated tooling is shown in the sketch in Fig. 1. The retort consists of a channel framework of 0.063 in. thick 321 stainless steel with gussets of the same material welded to the flanges on 5 in. centers. The retort is sealed and made into a vacuum box by welding 0.020 in. thick sheets of 321 stainless steel to the outside edges of the upper and lower flanges of the channel framework.

Two ⅜ in. diam stainless steel tubes are welded into the aft end of the retort for a vacuum line and to provide a passageway for a thermocouple wire. The thermocouple wire extends through the tube into the retort and contacts the laminate at a selected location. A ¼ in. diam tube is welded into the forward end of the box and is used to supply argon gas for purging the retort.

A 1 in. thick plate of RA330 steel is positioned in the bottom of the retort to provide a stable base for the braze laminate details. This material is ideally suited for the purpose because of low carbon content and thermal stability. Ideally, braze plates are five inches larger in both length and width than the braze laminate, and 0.120 in. smaller than the inside dimensions of the retort.

An atmosphere barrier made of titanium alloy rests on the braze plate and completely encircles the laminate. The barrier is ½ to 1 in. wide with a height equal to the height of the laminate. The primary purpose of the barrier is to provide a seal ring around the laminate and protect it from undesirable atmosphere should a leak occur during the braze cycle. During the brazing operation the upper closure sheet (vacuum sheet) is pulled down under vacuum over the barrier thus providing the seal. The inside dimensions of the barrier are one inch larger than the braze laminate details; its outer dimensions are one inch smaller than the inside dimension of the braze retort.

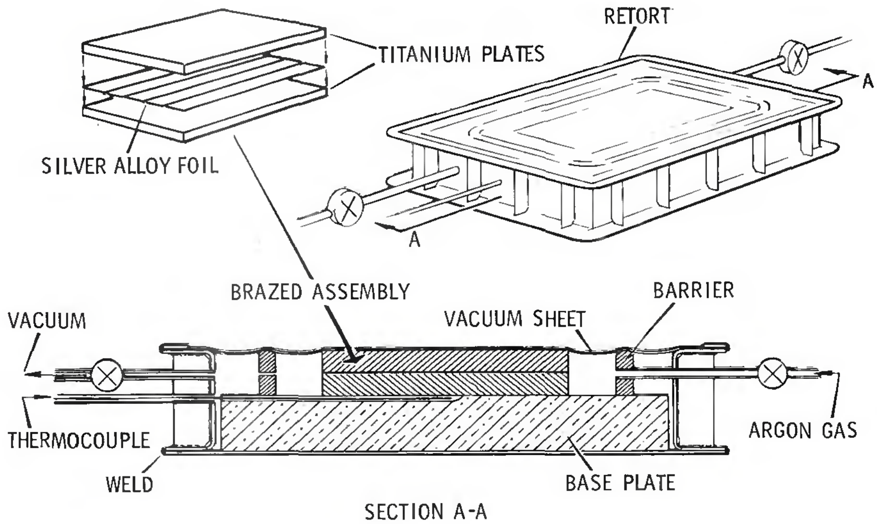


Fig. 1 — Brazing retort and assembly sequence

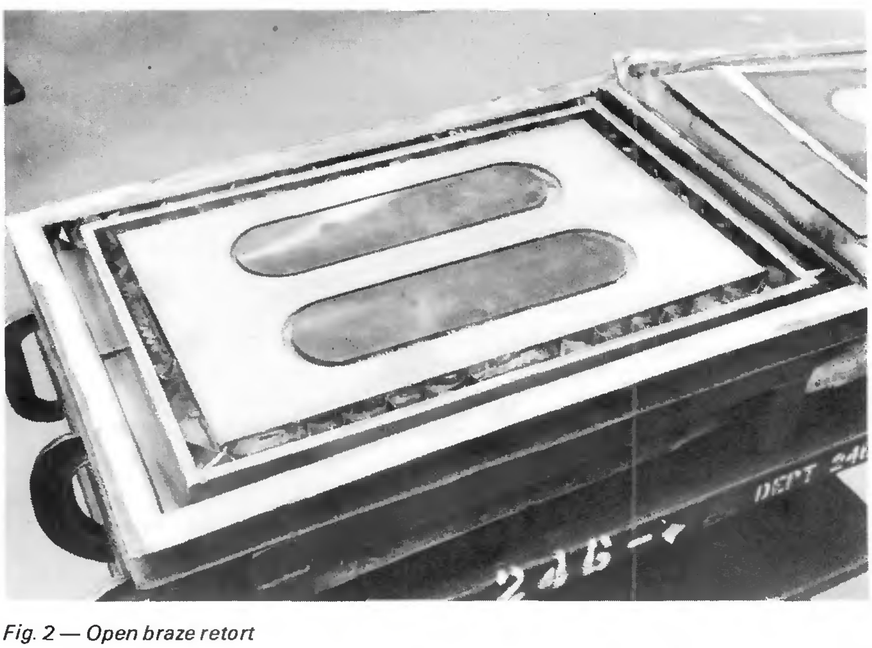


Fig. 2 — Open braze retort

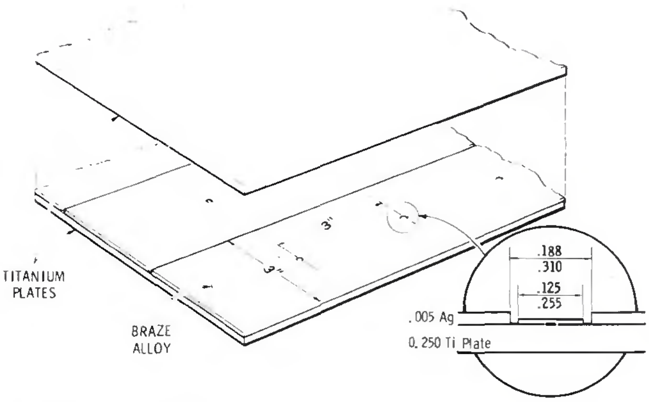


Fig. 3 — Typical braze assembly layup

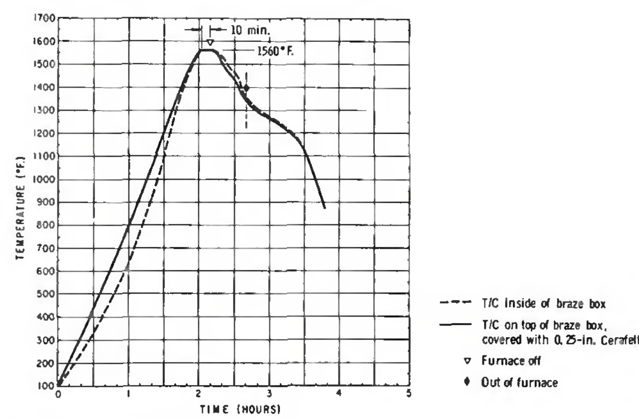


Fig. 4 — Typical brazing cycle

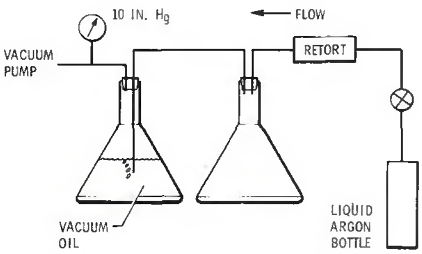


Fig. 5 — Retort leak detector

The barrier effectively excludes air which might leak through the retort weld due to the differential pressure created by flowing argon introduced within the barrier and the vacuum line located outside the barrier. Two small holes are drilled in the barrier in the end opposite the argon tube to allow the argon gas to flow out. An open braze retort is shown in the photograph in Fig. 2.

Other Tooling

The remaining tooling required for retort brazing are sheets of thin stainless steel, high temperature insulation, and filler blocks. Cover sheets covered with stop-off are used to separate the laminate from the braze block and vacuum sheet. The cover sheets and filler blocks are painted with stop-off and baked at 700 F to remove alcohol and moisture. Finally, a ¼ in. thick pad of high temperature insulation is placed on top of the sealed retort to help balance the heating and cooling rate of the titanium braze laminate. This is necessary to balance heat transfer through the 1 in. thick steel base plate.

Surface Preparation of Parts

Special surface preparation for titanium details include both machining and cleaning. Surface machining to reduce plate to the desired thickness is usually done by face milling. For final cleanup to remove irregularities belt sanding is used.

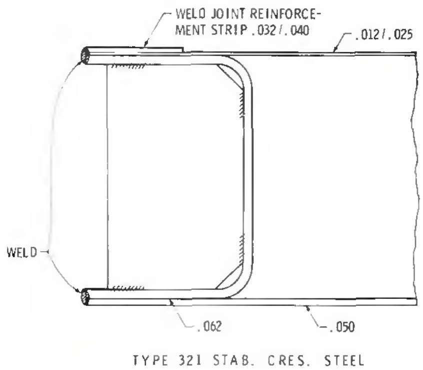


Fig. 6 — Retort design

The braze interface surface of flat plates is prepared most successfully by sanding, using an automatic belt sander with a controlled down feed. Desired surfaces are flat within 0.001 in. total indicator reading when held down with a vacuum chuck.

It has been demonstrated that surfaces finished between 40 and 250 rms are acceptable for brazing. Within this range there appears to be no appreciable change in brazing results.

The final step in surface preparation prior to the layup of details is chemical cleaning. The cleaning process includes degreasing, nitric-hydrafluoric acid pickle, nitric acid smut removal and rinse.

Brazing Filler Metal

The brazing filler metal for titanium is a material composed of 94.5Ag-5.0Al-0.5Mn. The filler metal used is 0.005 in. thick foil, 3 in. wide. Prior to layup of details, 5/32 in. diam holes are pierced on 3 in. centers in the filler metal foil sheet. These holes accommodate 0.002 in. × 1/8 in. diam stainless steel discs. The steel discs are used as spacers to ensure a consistent thickness braze line in the finished product. When the brazing filler metal is in a liquid state under pressure in the braze cycle, it is conceivable that alloy flow-out could be excessive in localized areas. The spacer discs maintain desired braze joint thickness.

The brazing filler metal used during the program was received in 16 separate heats totaling approximately 1700 troy ounces. Chemical analysis indicated silver content ranged from 93.55 to 94.41%, aluminum from 5.02 to 5.71% and manganese from 0.49 to 0.71%. Tramp elements were maintained very low.

Layup of Details for Brazing

Brazing filler metal is laid in strips on the interface surface of the titanium details. The edges of the alloy are butted together, being careful to avoid overlaps or excessive gaps. A typical layup is shown in Fig. 3. The brazing filler metal is locally tack welded to the surface of the titanium plate; the steel spacer discs are centrally located in the pierced holes and tack welded to the titanium plate. At this point the remaining details are assembled into the laminate.

Brazing filler metal flow is retarded in parts with flush edges by a metallic strip tack welded around the periphery of the part. The 0.002 in. metallic strip is coated with stop-off. At this point the assembled details are loaded into the clean retort and the upper closure sheet (vacuum sheet) is welded. All tubing and valves are carefully cleaned prior to each brazing operation.

Brazing Procedures and Parameters

Leak check prior to the braze operation is accomplished by pulling a partial vacuum of less than 1000 microns in the retort followed by a 30 min monitored hold period. If vacuum is maintained in the micron range for this period of time, the retort is considered acceptable for a braze run.

The braze retort is completely purged immediately before loading into the furnace. Purging is accomplished using argon gas from a high purity liquid container. After purging, a partial vacuum of 10 in. Hg is pulled on the retort and argon is flowed through the retort at a rate of 10 cfh. The retort is level-positioned in a furnace preheated to 1200 F and the braze cycle is started. Furnace temperature is increased and the contents of the retort are heated to 1560 F. This temperature is held until thermal stability is achieved; then the furnace is turned off.

The retort is cooled in the furnace to 1400 F, then removed and air cooled to a temperature suitable for easy handling. A typical braze cycle is shown in Fig. 4. At the beginning of the braze cycle, argon is introduced at a rate of 10 cfh with a vacuum of 10 in. Hg, until the temperature reaches 800 F. At this point the argon supply is shut off and the vacuum is maintained at 10 to 15 in. Hg. After achieving a near static condition above 800 F, the retort is constantly monitored for leaks using the apparatus shown in Fig. 5. The leak detection system becomes operational when the argon supply is cut off. A slow steady stream of bubbles, indicating outgassing and expansion, continues until approximately 1200 F where stability is approached. The bubbles at this point slow to approximately 40 per minute. A sharp increase in bubble rate would indicate a leak in the retort. The empty flask is used as a safeguard against oil entering the retort in case of a malfunction in vacuum equipment or valves. In the event a leak develops, argon gas can be admitted through the retort to prevent contamination of the assembly.

Discussion

Improvements in the retort design were prompted by failures to braze due to leaking in some retorts. The seal weld of the vacuum sheet occasionally failed due to wrinkling. This problem was solved by adding a reinforcement strip (Fig. 6) on top of the vacuum sheet at the seal weld location. The reinforcement strip increased the mass at the weld preventing thinning at the toe of the weld in the vacuum sheet.

Glass cloth was originally used as stop-off material between the titanium and stainless steel foil. As the size of the braze laminate assemblies increased, the quantity of glass cloth was also increased and outgassing from this source became excessive. The use of glass cloth was abandoned and baked-out stop-off was substituted successfully.

Purging of atmosphere from the pocket areas of the large braze laminate assemblies proved ineffective with the purging system shown in

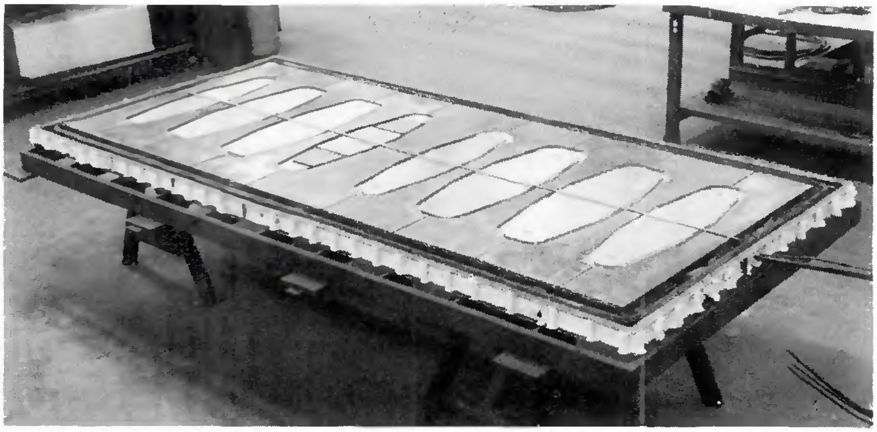


Fig. 7 — Brazed assembly (4 × 10 ft) in open retort

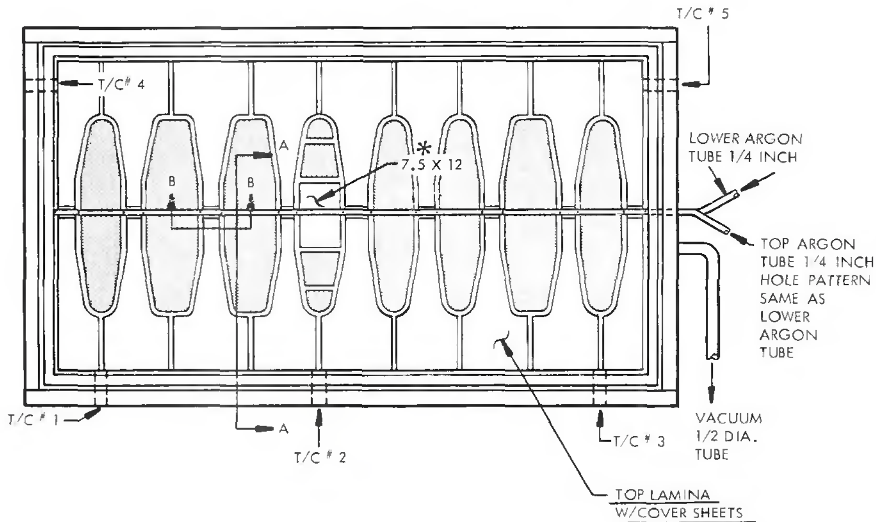
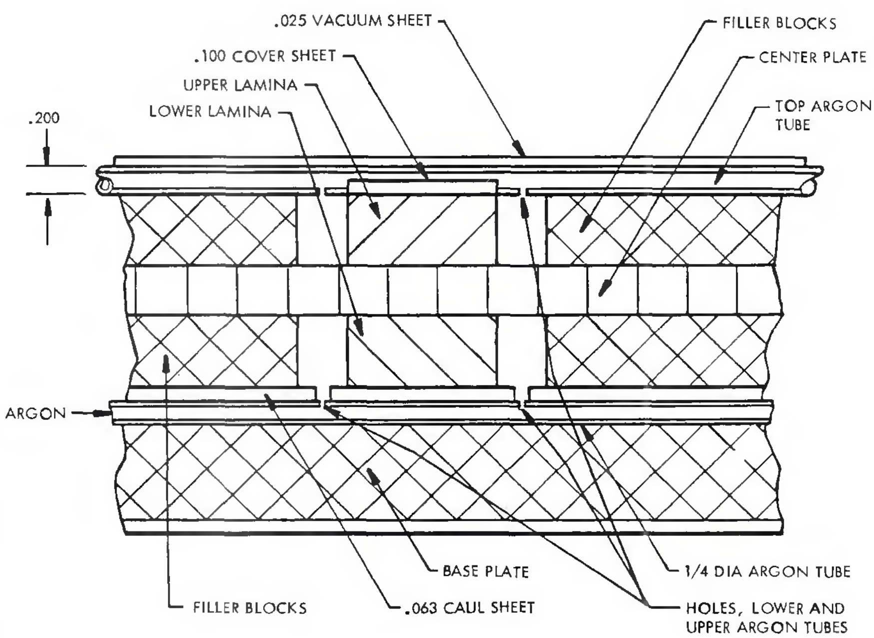


Fig. 8 — Final retort braze assembly without vacuum sheet



SECTION B B

Fig. 9 — Retort purging system (Section B-B of Fig. 8)

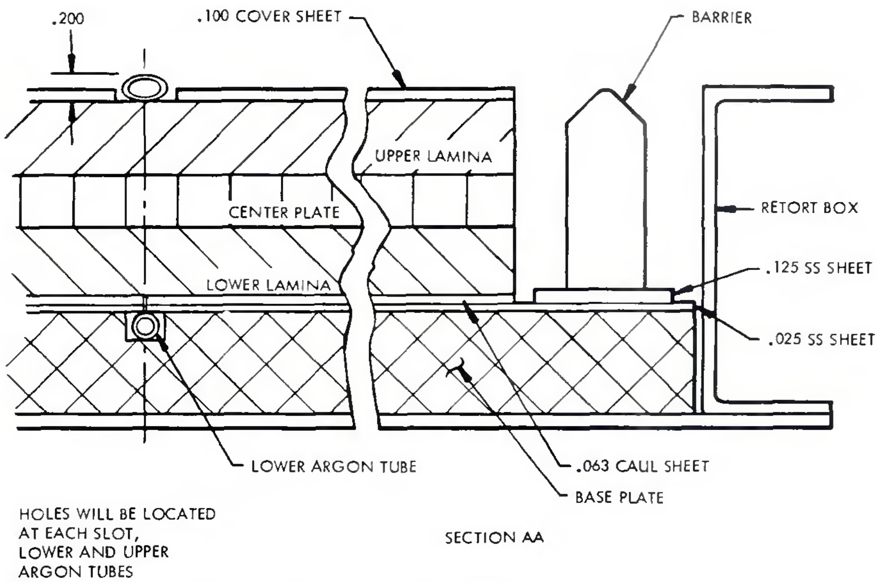


Fig. 10 — Retort purging and barrier system (Section A-A of Fig. 8)

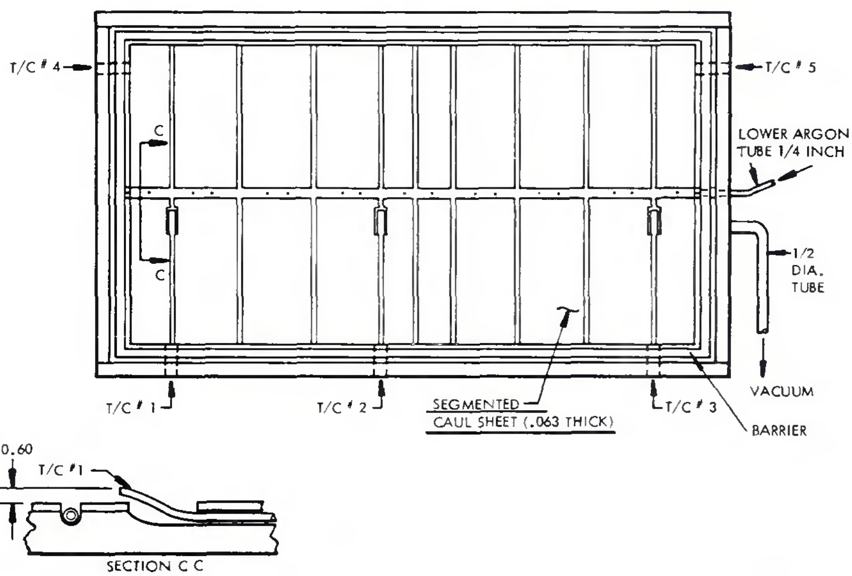


Fig. 11 — Braze retort

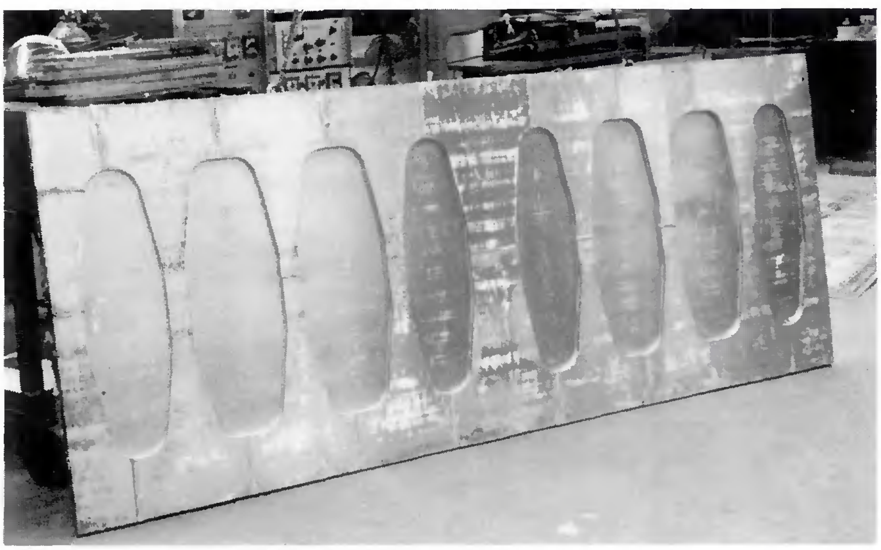


Fig. 12 — Braze assembly (4 × 10 ft)

Fig. 1. In order to adequately purge the pocket area, top and bottom of the 4 × 10 ft. braze laminate (Figs. 7, 8, 9 and 10) argon gas was piped through ¼-in. diam cres steel tubing to the center of each pocket to create an argon gas sweeping system.

In Fig. 8 the retort without the vacuum sheet is shown in schematic to detail the arrangement of the braze laminate assembly, filler blocks, cover sheets, argon tube purging system, T/C location, etc. Sections B-B and A-A (Figs. 9,10) further detail the argon gas purging system. The tubes on top and bottom of the braze titanium lamina constitute a manifold system with variable size holes to equalize quantity of argon gas flowing to each groove created by the upper and lower surfaces and filler blocks. The top tube was formed to an oval shape to minimize the wrinkling effect on the vacuum sheet. The holes in the barrier to allow the argon gas to escape were drilled in the same end of the barrier to which the vacuum tube was attached.

The argon flow created by this modification was visually checked by building a full scale wood mockup with a plexiglass vacuum sheet using smoke to trace the gas flow. The system proved to be very effective in actual brazing.

The system used to monitor the temperature of the braze laminate assembly was changed as the retort package increased in size. In lieu of welding ¼ in. diam tubes into the outside of the retort and running to the exterior of the furnace, sealed tubes were welded to the inside of the retort and extended to the thermocouple (T/C) location. With the use of sheathed T/C, the handling and sealing problems were reduced.

In Fig. 11 a schematic drawing of the retort for the 4 × 10 ft braze assembly is shown with only the base plate, barrier, T/C tubes and caul sheets in place. T/C No. 1, 2, and 3 were located and preformed so the ends of the T/C tubes would contact the lower surface of the center titanium lamina, i.e. the lower braze joint. The ends of T/C No. 4 and 5 tubes were located in the upper surface of the base plate. All of the T/C tubes were routed through grooves cut in the base plate.

An additional T/C was imbedded in a 2 × 6 × 6 steel block which was placed on the top center of the vacuum sheet during brazing. During the braze cycle the T/C toward the outer edges of the retort package indicated faster temperature rise than T/C No. 2. As the retort package reached the design maximum temperature the furnace temperature was lowered to slightly above the maximum brazing temperature and the T/C readings allowed to stabilize uni-

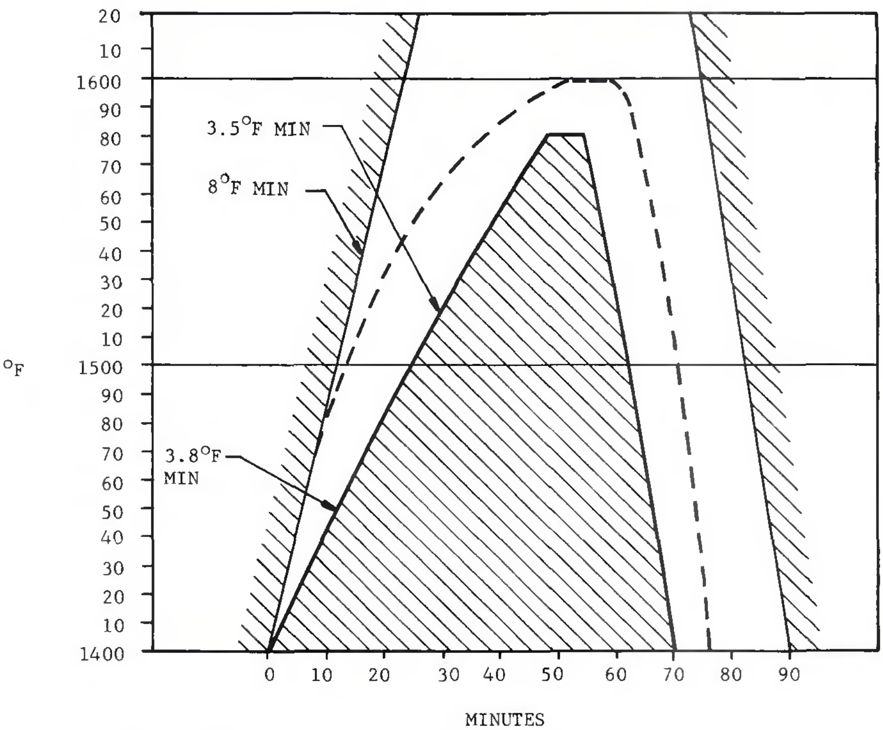


Fig. 13 — Brazing cycle time-temperature boundaries

formly at near the maximum desired brazing temperature.

On small braze assemblies and retort packages heating rate was not a problem and good braze joints were achieved. As the size of the braze assemblies increased to the maximum size of 0.600/0.400/-0.600 × 48 × 120 in. the retort package, including the rack to provide a level position, exceeded 5000 lb. On the first attempt to braze a laminate of this size, the insulation was used on top of the retort and the temperature was brought up slowly to 1550 F. The result was an inadequate braze. The total time from 1400 F to 1550 was 60 min for an average heat rate of 2.5 F/min.

Using small laboratory specimens and studying previous time-temperature curves it was determined that a heating rate of 4 F/min would be adequate. Also it was determined that the slower heating rate caused increased reaction between the titanium and brazing filler metal and the temperature required for an adequate braze was raised (Ref. 2).

For the second full size laminate (1.6 × 48 × 120) the insulation was removed from the retort, the furnace preheated to 1400 F and an average heat rate of 3.8 F/min was accomplished. An excellent braze was obtained with 100% fillets in all pockets. (See Fig. 12).

To establish the brazing cycle time-temperature boundaries necessary to achieve an adequate braze joint for all brazed titanium assemblies would be impossible due to the many variables. Based on the size and weight of assemblies brazed on this program the boundaries in Fig. 13 are offered as a starting point. For the brazing filler metal used, maximum and minimum heating rates are shown. Heating rates faster than 8 F/min produce good wetting though not enough reaction zone between the filler metal and the titanium to offer good corrosion resistance. Heating rates slower than 3.8 F from the solidus to the liquidus temperatures do not produce a good quality braze. Experience has shown that the brazing filler metal exhibits excessive aluminum segregation and gross voids are created in the braze line (Ref. 2). Minimum braze temperature is shown at 1580 F with a 7 min hold time. Total time above 1400 F (near solidus temp) of 50 min is adequate although large retort packages will not heat and cool at a rate for this to be a problem. The total time above 1400 F should be a minimum of 50 min to insure adequate reaction time between the brazing filler metal and titanium alloy.

Conclusions

1. The details of tooling and retort design, preparation and layup of details, and brazing procedures have been described for producing large area (4 × 10 ft) laminated titanium brazed assemblies.
2. The braze assembly thus produced conformed to test requirements for a fail-safe, primary airframe application.
3. The feasibility of producing laminated titanium structural components of significant size has been demonstrated.

Acknowledgment

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