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ADVANCED FABRICATION TECHNOLOGY FOR HIGH SPEED AIRCRAFT STRUCTURES

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ABSTRACT

Advanced fabrication processes have been developed at the NASA Langley Research Center for producing titanium, aluminum matrix composite and titanium aluminide structures for application on future supersonic and hypersonic aircraft. Evaluation of the processes for fabricating Ti-6Al-4V titanium alloy and Borsic®/aluminum (Bsc/Al) structures intended for supersonic aircraft applications included the design, fabrication, ground testing, and Mach 3 flight service evaluation of upper wing panels on the NASA YF-12 airplane. Evaluation of the process developed for fabricating thin gage Ti-14Al-21Nb titanium aluminide structures for application on future hypersonic aircraft consisted of the fabrication and evaluation of small structural elements.

An overview of the development of the weldbrazing process for fabricating Ti-6Al-4V skin-stiffened panels, a brazing process for fabricating Bsc/Al titanium honeycomb core panels, and the Enhanced Diffusion Bonding (EDB) process for fabricating Ti-14Al-21Nb titanium aluminide structural elements are presented. Data presented include the shear strengths of full-scale weldbrazed Ti-6Al-4V skin stiffened and Bsc/Al titanium honeycomb core sandwich panels designed to meet the requirements of an upper wing panel on the NASA YF-12. These results verified that the materials, fabrication processes and structural concepts were qualified for Mach 3 flight. Shear strengths of each of the panel concepts following flight service evaluation are also reported. Comparisons made with the cost and weight of the original wing panel indicated that the weldbrazed titanium panels resulted in a 15-20 percent cost savings and the brazed Bsc/Al panel showed a 30 percent weight savings. Test data presented on the Enhanced Diffusion Bonded Ti-14Al-21Nb titanium aluminide sandwich structure consisted of the results of edgewise compression tests conducted at ambient and 811 K (1000°F). These data show that the strengths of the EDB joints were sufficient to develop stresses in the Ti-14Al-21Nb face sheets of the sandwich structure which were above the yield strength of the material. Also reported are the results of metallurgical analyses conducted on the joints produced by each of the processes developed.

INTRODUCTION

The successful development of high speed aircraft having a sustained supersonic or hypersonic cruise capability is highly dependent on the development of lightweight, high temperature structures. As a result, the Materials Division at the NASA Langley Research Center has been conducting research for over 20 years on the development and evaluation of lightweight, high-temperature monolithic and composite materials as well as the development of advanced fabrication technology to effectively incorporate these materials into efficient structural concepts.

In support of the NASA Supersonic Cruise Aircraft Research (SCAR) program, studies were conducted to develop advanced fabrication methods for the effective incorporation of titanium and continuous fiber reinforced aluminum metal-matrix composites into lightweight primary structure suitable for use on Mach 3 supersonic cruise aircraft. To focus and validate the fabrication technology developed, panels were fabricated to meet the design requirements of an upper wing panel on the Mach 3 NASA YF-12 aircraft. This program was a combined effort involving the NASA Langley Research Center (LaRC), the NASA Dryden Flight Research Center, and a contractual activity with the Advanced Development Projects (ADP) Division of the Lockheed-California Company.

Due to the undefined structural requirements and the lack of availability of materials having the desired specific elevated temperature properties needed to meet the stringent requirements of the National Aero-Space Plane (NASP) program, fabrication studies were conducted using available titanium aluminide intermetallic materials. The fabrication technology developed using these model materials could serve as a basis for fabrication of titanium aluminide and titanium aluminide metal-matrix composite structures when the materials become available.

This paper presents an overview of the development and evaluation of three fabrication processes developed at the NASA Langley Research Center: the weldbraze process developed for fabricating titanium skin stringer structure, a brazing process developed for fabricating Borsic®/aluminum (Bsc/Al) metal-matrix composite structure, and the Enhanced Diffusion Bonding (EDB) process developed for fabricating lightweight titanium aluminide honeycomb-core sandwich structure. The former two fabrication processes are intended for application on future supersonic (Mach 2.4 - 3.4) aircraft while the later fabrication process is intended for application on future hypersonic (> Mach 5) vehicles. Reported herein are the development and evaluation of the three fabrication processes which include a metallurgical investigation of the interaction of the filler metal with the base material as well as the test results of panels designed to meet the primary structure requirements of the YF-12 and small structural test elements intended for application on future hypersonic cruise aircraft.**

®Borsic is a registered trade name of United Aircraft Products, Inc.

DESIGN REQUIREMENTS

YF-12 Panel Design

The panel selected for fabrication and evaluation in support of the SCAR program was an upper wing panel on the Mach-3 YF-12 aircraft. The panel 71.1 cm (16 in x 28 in). The original panel on the aircraft was an integrally stiffened skin riser type machined from titanium plate and weighed 3.86 kg (8.5 lbs) (ref. 1). The location of the panel on the NASA YF-12 is shown by the rectangular outlines in figure 1 . The weldbrazed titanium and brazed Bsc/Al titanium honeycomb-core sandwich panels fabricated in this study were designed to meet the structural requirements of the original panel on the aircraft and to be compatible with the aircraft substructure. The principal design requirement of the original panel was ultimate shear strength at both room temperature and 589 K (600°F). In this study the weldbrazed titanium panel was designed to have an ultimate shear strength of 680 kN/m (3885 lb/in) at room temperature and 425 kN/m (2425 lb/in) at 589 K (600°F). The brazed Bsc/Al titanium honeycomb-core sandwich panel was designed to meet slightly lower requirements which were an ultimate shear strength of 525 kN/m (3000 lb/in) at room temperature and 328 kN/m (1875 lb/in) at 533 K (500°F).

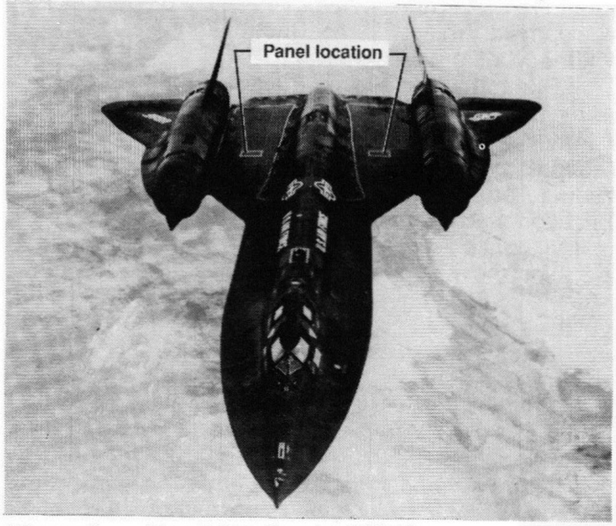


Figure 1. - Panel location on YF-12.

NASP Structural Element Design

The titanium aluminide honeycomb-core sandwich specimens fabricated in this study were targeted to sustain a compression load index of 525 kN/m (3000 lb/in) at ambient temperature based on preliminary design requirements for hypersonic airframe structures. These specimens were fabricated to demonstrate the ability of a titanium aluminide structural element fabricated using the EDB process to meet this requirement. Structural panels on the NASP aircraft are expected to operate at service temperatures exceeding 1089 K (1500°F). Due to the limitations of currently available materials, structural element specimens made from these model materials were fabricated and tested at both room temperature and 811 K (1000°F).

FABRICATION DEVELOPMENT AND TEST PROCEDURES

I. Weldbrazing of Ti-6Al-4V Titanium Alloy

Process Development

Weldbrazing is a process developed at the NASA Langley Research Center that combines the use of resistance spotwelding and brazing to produce joints which have been shown to have superior properties in tensile shear and fatigue compared to joints produced by riveting or spotwelding alone for joining Ti-6Al-4V titanium alloy sheet materials (ref. 2,3). Resistance spotwelding is used to position and aline the parts and to establish a suitable faying surface gap for brazing. To complete the process for joining Ti-6Al-4V sheet material, 3003 aluminum braze alloy is positioned adjacent to the edge of the faying surface gap and the assembly is positioned in a vacuum furnace and heated to the brazing temperature of approximately 950 K (1250°F) in a vacuum of 1.33 mPa (10^{-5} torr). Fixturing provided by the spotwelds is sufficient to maintain alignment of the assembly. Therefore, no tooling is required for brazing. Upon melting, the braze alloy is drawn into the faying surface gap by capillary action to form a continuous, hermetically sealed joint.

To investigate the viability of using the process to fabricate flight quality hardware for supersonic aircraft, a contract was awarded to the Lockheed-California Company - Advanced Development Projects (ADP) to design, fabricate, and test full-scale panels intended for flight service evaluation on the upper wing surface of the NASA YF-12 airplane.

Panel Concept and Fabrication

The general configuration and construction details of the weldbrazed panel assembly are shown in figure 2 . The panel consists of an annealed Ti-6Al-4V titanium alloy skin chemically milled in the center to a thickness of 1.78 mm (0.070 in.), and thirteen Ti-6Al-4V "Z" type stiffeners formed from 1.27 mm (0.050 in.) sheet. The stiffeners were spotwelded to the skin using a welding schedule that produced a 0.08 mm - 0.10 mm (0.003 in - 0.004 in.) weld nugget expansion gap at the faying surface. Narrow strips of 0.41 mm (0.016 in.) 3003-H14 aluminum braze alloy sheet were scarfed to a knife-edge along one side and were wedged in the faying surface gap at the foot of each stiffener to hold them in place during brazing. Brazing was accomplished in a vacuum furnace at 972 K (1290°F) for 10 minutes at a vacuum of 1.33 mPa (10^{-5} torr). A total of five panels were fabricated for test and evaluation. The fabrication processes and destructive and nondestructive quality assurance procedures used to produce these panels and specimens are described in detail in reference 1.

** Identification of commercial products in this report is used to adequately describe the material. The identification of these commercial products does not constitute official endorsement, expressed or implied, of such products or manufactures by the National Aeronautics and Space Administration.

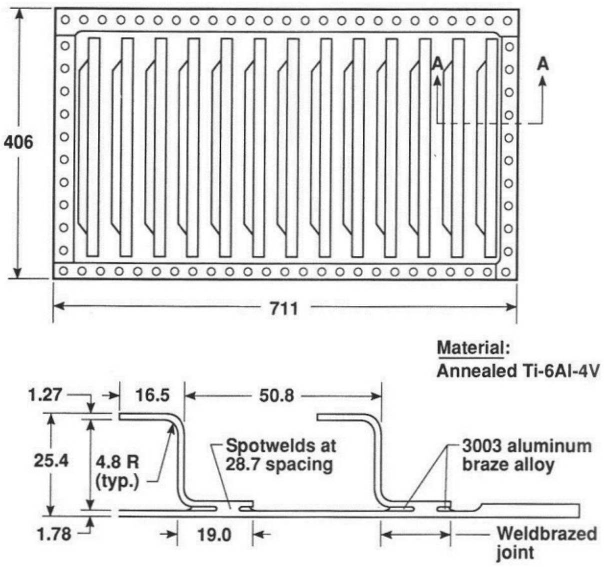


Figure 2. - Configuration of weldbrazed titanium skin-stiffener panels. Dimensions are given in millimeters.

Panel Tests

In order to demonstrate that the weldbraze panels met the design requirement of the YF-12 airplane and to qualify an additional panel for flight service, four panels were tested to failure in shear at Lockheed ADP. Two of the panels were tested in the as-fabricated condition and two were exposed at the NASA Dryden Research Center to 589 K (600°F) prior to testing. One as-fabricated and one exposed panel were tested to failure at both ambient and at 589 K (600°F) temperatures. The panels were tested to failure in shear using a specially designed picture-frame shear test fixture. This test fixture was designed to apply a tensile load to diagonally opposite panel corners using pin-jointed shear frames and clevises. A photograph of a strain-gaged panel mounted in the picture-frame test fixture having pinned corners is shown in figure 3 . Loading of the panels was done incrementally to permit time to record strain gage readings for both proof loading and loading to failure. Strain gage readings indicated that a state of pure shear was achieved during panel loading.

For the 589 K (600°F) test, the fixture was enclosed within a heating apparatus which employed banks of quartz lamps for heating (ref. 4). Air circulating fans and baffles were used to assure uniform heating [±11 K at 589 K (±20°F at 600°F)].

Following flight qualification testing of the four panels, an additional weldbrazed panel was proof loaded to two-thirds of design ultimate shear at ambient temperature and was installed on the YF-12 aircraft for Mach-3 flight testing.

II. Brazing of Bsc/Al

Process Development

In an attempt to exploit the potential offered by the high specific material properties of aluminum metal-matrix composites to reduce the weight of aircraft structures, studies were initiated at NASA LaRC to develop fabrication processes for the efficient incorporation of these materials into aircraft structures. The use of both continuous fiber reinforced boron/aluminum (b/Al) and Borsic/aluminum composites were evaluated. The Borsic filaments used to make the aluminum matrix composites were essentially the same as the boron filaments with the exception that the outer surface of the fiber was coated with silicon carbide. Intrinsic material properties which limit the fabricability of these materials such as formability, machinability, and degradation in properties due to thermal exposure were considered during process development. Based on these studies (ref. 5), brazing was selected as the process having the highest potential for fabricating efficient structures. Borsic fiber composites with a 6061 aluminum alloy matrix were selected for study rather than boron fiber composites because the properties of the preconsolidated Bsc/Al composite sheet were less affected by exposure to the thermal environment associated with brazing than were b/Al composite sheets. A honeycomb-core sandwich structure was selected as the structural concept to be evaluated due to its high structural efficiency and to avoid the need for shaping the very stiff Bsc/Al composite sheets. Aluminum-silicon braze alloy 4047 was selected to join the Bsc/Al composite face sheets to the titanium honeycomb core. This braze alloy was selected due to its relatively low melting range of 850 - 855 K (1070°-1080°F) which minimizes thermal degradation of the Borsic filaments. In addition, the braze alloy exhibited good wetting characteristics on both the Bsc/Al face sheets and the titanium honeycomb core and exhibited good joint strength.

In order to demonstrate that the brazing process for fabricating Bsc/Al titanium honeycomb-core sandwich structure was capable of producing flight quality hardware, upper wing panels for the YF-12 airplane were designed and fabricated at the NASA Langley Research Center for both flight qualification testing and flight service evaluation on the YF-12.

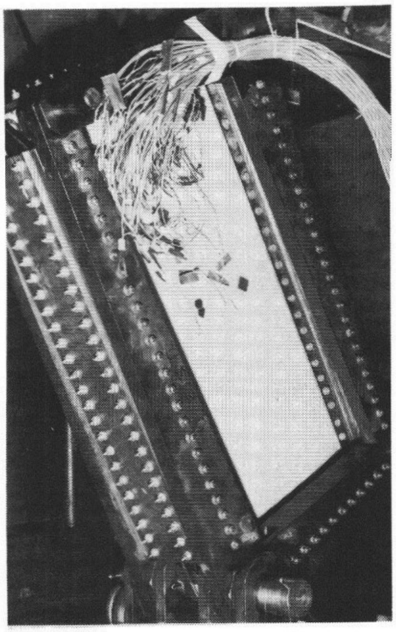
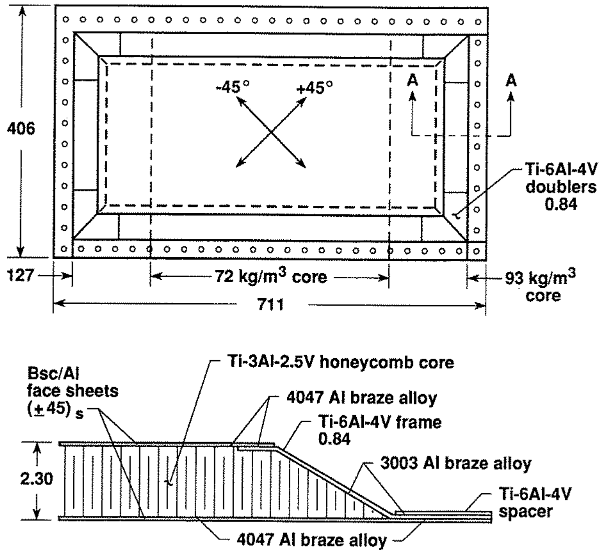


Figure 3. - Panel shear test fixture.

Panel Concept and Fabrication

The design concept for the Bsc/Al titanium honeycomb-core YF-12 panel is shown in figure 4. The requirements of retrofitting this panel on the YF-12 imposed severe limitations on the effective utilization of the Bsc/Al composite high stiffness and directional properties compared with those of titanium. Detailed analyses of the wing structure indicated that the shear stiffness of the replacement panel could be increased by 25 percent without overloading adjacent structures. It was also determined that the ultimate shear strength requirements could be reduced by approximately 23 percent and still satisfy all critical flight loading requirements. Consequently the design concept shown employed upper and lower face sheets of Bsc/Al with orientation of the continuous filaments in the +45°, -45°, -45°, +45° direction. The matrix of the composite was 6061 aluminum alloy with a layer of 1100 aluminum alloy preconsolidated on one surface to limit diffusion and interaction of the braze alloy with the constituents of the composite material. Ti-6Al-4V titanium alloy sheet material was used to fabricate the edge member frame and Ti-3Al-2.5V titanium alloy foil was used to fabricate the honeycomb core.



Section A-A

Figure 4. - Configuration of Borsic/aluminum honeycomb-core sandwich panels. Dimensions are given in millimeters.

Panel components were assembled in a two-step vacuum brazing operation (ref. 6). The first step consisted of brazing the titanium honeycomb core and doublers to the frame, and the second step involved brazing the Bsc/Al face sheets to the brazed titanium core/frame subassembly. Because first-step brazing involved only titanium components, a braze alloy was selected that had a higher melting temperature and better wetting characteristics than 4047 aluminum braze alloy. The braze alloy selected was 3003 aluminum alloy which was used successfully by the Boeing Company to fabricate titanium sandwich structure for the U.S. Supersonic Transport Program (ref. 7). Second-step brazing employed 4047 aluminum alloy to braze the Bsc/Al face sheets to the titanium core/frame subassembly for reasons previously discussed.

Prior to assembly for brazing, all components were chemically cleaned according to established procedures. Assembly for first-step brazing was initiated by positioning the core within the frame. Positioning was maintained by tackwelding titanium foil strips to both the cell walls of the honeycomb core and the frame. The titanium doublers and a 0.127 mm thick (0.005 in) strip of 3003 aluminum braze alloy were then tackwelded to the flanges of the frame. The assembled components and the braze tooling are shown in figure 5. The tooling consists of an upper and lower platen, a stainless steel caul sheet, titanium release sheet, titanium honeycomb core tooling, and a stainless steel bladder. Strips of 0.25 mm thick (0.010 in) 3003 aluminum braze foil were placed between the honeycomb core and the release sheet during assembly. Brazing was accomplished by heating the tooling and components in a vacuum furnace to a temperature of 961 K (1270°F) for a period of 5 minutes at a pressure of 1.33 mPa (10^{-5} torr). Proper contact between mating parts was maintained during brazing by pressurizing the stainless steel bladder with helium to 27.6 kPa (4 psi). The brazed joint between the core and frame was established by the braze melting and flowing down the nodes of the honeycomb core. Capillary action of the molten braze resulted in uniform filleting between the core and frame. Brazing of the core to frame in a separate operation provided for visual inspection for disbonds and facilitated rebrazing if necessary.

For the second-step braze assembly, the four-ply outer Bsc/Al face sheets and 0.2 mm thick (0.008 in) 4047 aluminum braze foil were positioned on the brazed titanium core/frame subassembly with resistance tackwelds. The lower face sheet and braze alloy were held in place with titanium foil straps tackwelded to the frame across each corner. The assembled panel was placed in the tooling as shown in figure 6. The tooling was essentially the same as that shown in figure 5 with the exception that it was inverted and a larger pressurized bladder was used to apply pressure over the entire face sheet area. Suitable ports were provided through the chamber

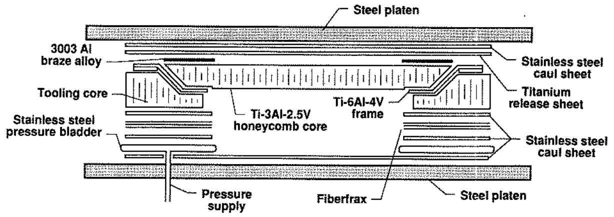


Figure 5. - Cross section of tooling for first-step brazing.

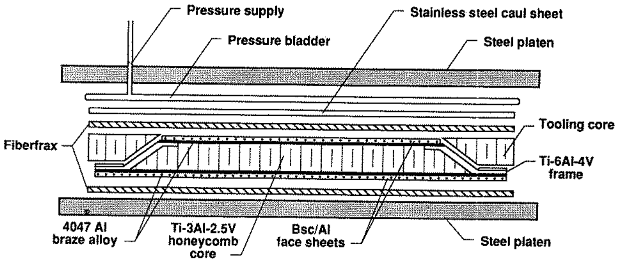


Figure 6. - Cross section of tooling for second-step brazing.

wall of the furnace to extend the thermocouples and pressure line of the bladder to the associated control and recording equipment. Following evacuation of the vacuum furnace to a pressure of 133 x 10^{-6} Pa (10^{-6} torr), the assembly was slowly heated to a temperature of 839 K (1050°F). Thermal equilibrium was established by holding the temperature at 839 K (1050°F) for approximately 10 minutes prior to heating to the brazing temperature of 864 K (1095°F). When the face sheet temperature reached 864 K (1095°F), power to the heating elements was turned off and the inert-gas cooling system was activated. Circulating helium gas cooled the panel to 839 K (1050°F) in approximately 10 minutes. Gas cooling was then discontinued and the panel was furnace-cooled to ambient temperature.

Panel Tests

The panel test procedures for the brazed Bsc/Al panels were the same as that listed in the weldbrazed panel test procedures. Four Bsc/Al panels were tested to qualify the integrity of the panel concept for flight and one panel was proof loaded and placed on the YF-12 for flight service evaluation.

III. Enhanced Diffusion Bonding (EDB) of Titanium Aluminide

Process Development

Enhanced Diffusion Bonding is a joining process developed at NASA LaRC which uses a eutectic liquid phase to assist or enhance the diffusion bonding of metallic materials (ref. 8). For titanium-base materials, a thin intermediate material is placed between the mating titanium surfaces to be joined. When heated above the titanium/intermediate material eutectic temperature for a sufficient period of time, this intermediate material interdiffuses with the titanium to form a eutectic composition. As a result, a eutectic liquid forms and fills the gaps present at the joint interface. This liquid phase enhances diffusivity and ensures intimate contact at the joint interface without the high bonding pressures and close surface tolerances required by conventional diffusion bonding. With continuing solute diffusion, the melt composition becomes titanium-enriched causing an increase in the melting temperature and eventual isothermal solidification. Continued holding at temperature permits solid-state diffusion to dilute the solute concentration even further resulting in improved mechanical properties of the joint.

The use of foil gage materials for fabrication of lightweight structures necessitates that any deleterious effects associated with metallurgical interaction between the intermediate material and the base material be minimized. In a honeycomb-core sandwich structure, the face sheet/core contact area comprises less than 2 percent of the total panel surface area. Hence, in order to minimize both the weight penalty and any potential deleterious metallurgical interaction effects associated with the intermediate or EDB material, the EDB material was applied to only those areas actually needed for joint formation, ie., the edges of the core.

Based on prior research (ref. 9) and evaluations of titanium-based phase diagrams, the intermediate material selected for EDB was copper. The initial research focused on developing an optimized plating process for localized deposition of the intermediate copper material onto the edges of the core. The process selected involved a selective removal of maskant / tank plating technique. In order to validate that the EDB process was capable of producing efficient structural concepts, edgewise compression test specimens were fabricated and evaluated.

Structural Element Concept and Fabrication

Model materials based on expected titanium aluminide (Ti_xAl) matrix compositions were utilized in the study. An available Ti_3Al alloy (Ti-14Al-21Nb) was selected as the face sheet material and an alpha-beta titanium alloy (Ti-3Al-2.5V) was used for the honeycomb-core material. The face sheet material was hot rolled from ingot metallurgy plate stock to 0.51 mm (0.020 in) thick sheet. The honeycomb core was fabricated using 0.051 mm (0.002 in) thick foil which was resistance spot welded at the nodes to form a 6.35 mm (0.25 in) square cell core configuration. The edges of the honeycomb core were machined parallel to a core depth of 15.2 mm (0.6 in) and the cell walls were corrugated.

In order to control the application of the intermediate copper material onto the edges of the core only, a process was developed using a maskant and tank electroplating technique. This technique consisted of masking the entire honeycomb core material with a lacquer maskant as shown in figure 7. After drying, the maskant coating was mechanically removed from just the edges of the honeycomb core. The exposed edges of the core were then electroplated with the desired amount of intermediate copper material using the tank plating process. After electroplating the exposed core edges, the maskant was removed from the remainder of the core using a lacquer thinner. Using this technique, intermediate copper material was plated onto the edges of the Ti-3Al-2.5V honeycomb core in thicknesses ranging from 0.05 - 125 μm (2 - 5000 μin).

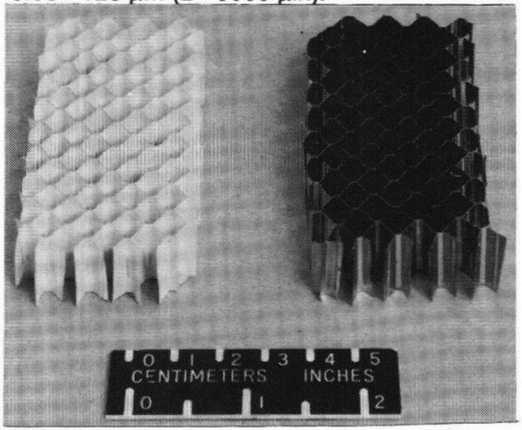


Figure 7. - Tank plated honeycomb core before and after maskant removal.

Figure 8 shows the typical layout for an EDB honeycomb-core sandwich panel. The panel components consist of two Ti-14Al-21Nb face sheets and a Ti-3Al-2.5V honeycomb core electroplated with the intermediate copper material on the edge of the core only. The electroplated honeycomb core was placed between the two face sheets and the assembled components were placed in a vacuum furnace between two flat steel platens. After evacuating the furnace below 1.33 mPa (10^{-5} torr) pressure, the panels were bonded at temperatures ranging from 1172 K - 1228 K (1650°- 1750°F) for 10 to 60 minutes. Following the bonding cycle, the bonded assembly was forced inert gas cooled to room temperature.

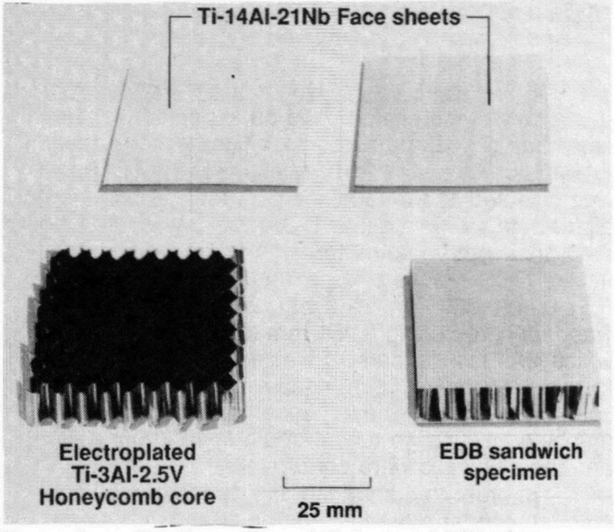


Figure 8. - Configuration of Enhanced Diffusion Bonded titanium aluminide honeycomb-core sandwich panels.

Structural Element Tests

The mechanical properties of the EDB honeycomb-core sandwich panels were evaluated using edgewise compression (EWC) tests. These tests determine the compressive properties of a honeycomb sandwich panel when loaded in a direction parallel to the plane of the face sheets. Figure 9 shows a typical EWC test specimen. Also shown are the mechanical end support clamps used to laterally support the EWC specimen ends and prevent localized end failures. Specimens were machined from larger EDB sandwich panels using water-cooled abrasive cut-off wheels. The dimensions of the EWC test specimens were nominally 16.5 cm long by 5.1 cm wide by 1.6 cm thick (6.5 in x 2.0 in x 0.64 in). The ends of the EWC specimens were machined flat and parallel to ensure uniform loading of the face sheets during testing.

The EWC specimens were tested in a specially designed high-temperature EWC test fixture (figure 10) (ref. 10) according to ASTM specification C364 (ref. 11). This fixture was contained within a 15 cm (6 in) inside diameter clamshell furnace. Load was provided by a 44.5 kN (10 kip) tensile machine. Through a load reversal mechanism, the EWC fixture converted the tensile load from the test machine to a compressive load on the specimen. EWC specimens were tested at room temperature and 811 K (1000°F). For the room temperature tests, strain was monitored with strain gages bonded to the specimen surface. For the elevated temperature tests, two diametric cut-outs in the furnace wall permitted the attachment of back-to-back water-cooled, high-temperature extensometers to the sandwich specimen to monitor specimen strain. Specimens were loaded to failure at a rate of 4.5 kN/min (1000 lb/min). Load, strain, and failure mode were recorded. Face sheet yielding was determined by the deviation in linearity of the load/strain curve. EWC strength was obtained by dividing the breaking load by the face sheet cross sectional area.

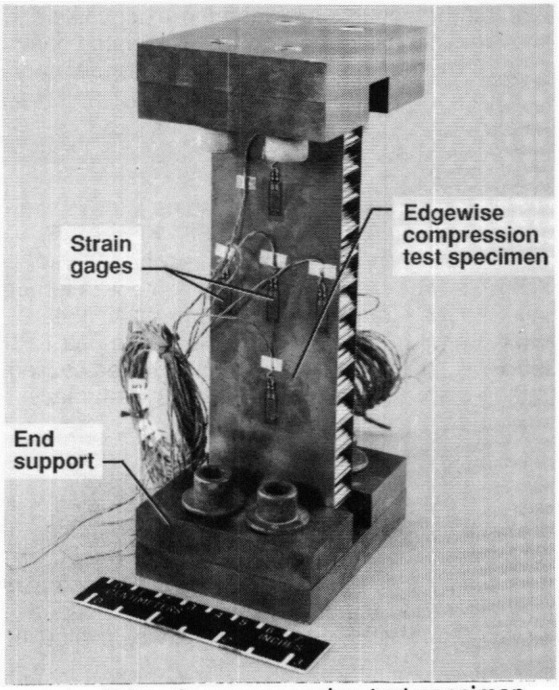


Figure 9. - Edgewise compression test specimen.

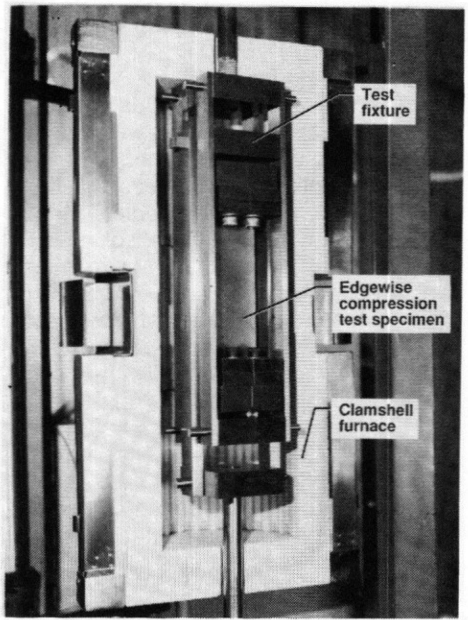


Figure 10. - Edgewise compression test assembly.

RESULTS AND DISCUSSION

II. Weldbrazed Ti-6Al-4V Titanium YF-12 Panels

Panel Test Results

The results of the shear tests of the weldbrazed Ti-6Al-4V skin stiffener panels are shown in figure 11. The as-fabricated panel tested at room temperature failed at 132 percent of design ultimate shear strength and the panel exposed to 589 K (600°F) for 100 hours failed at 126 percent. For the panels tested at 589 K (600°F), the as-fabricated panel failed at 180 percent of design ultimate shear strength and the panel previously exposed for 100 hours at 589 K (600°F) failed at 166 percent. The lower strength of the exposed panels was attributed to normal test scatter rather than adverse effects of exposure. This assumption was based on coupon data of weldbrazed samples not reported herein.

The weight of the weldbrazed Ti-6Al-4V panels was equivalent to that of the original panel. While no weight savings were achieved, substantially less material was required to fabricate the built-up sheet metal weldbrazed panel compared with that required for the original integrally machined structure. As a result of the improved material buy-to-fly ratio and due to simplified processing, it was estimated that the weldbrazed panels would result in a 15-25 percent cost savings compared to the cost of the original structure.

The panel subjected to flight service evaluation on the YF-12 accumulated 106 hours of flight time prior to testing. Of this total time, approximately 32 hours were spent at speeds above Mach 2.6 and approximately 25 hours were spent at speeds of Mach 3.0. The shear strength of this panel was 130 percent of design ultimate indicating no detrimental effects of flight service on the integrity of the structure. Thus, the weldbrazing process was demonstrated to be capable of fabricating flight quality structure meeting the requirements of Mach 3 flight.

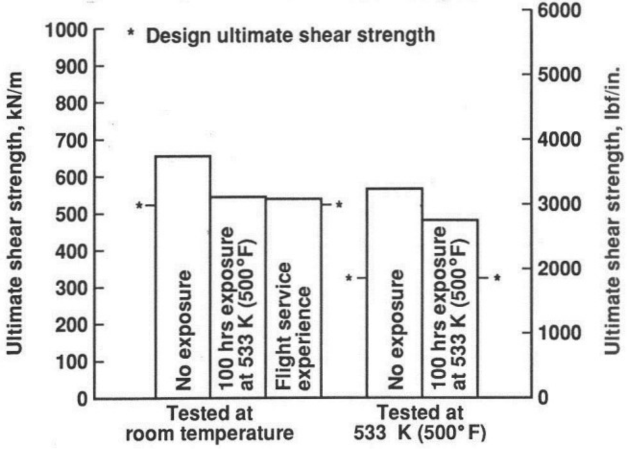


Figure 11. - Shear strength of weldbrazed titanium skin-stiffener panels.

Metallurgical Analysis

A typical metallurgical cross-section of a weldbrazed Ti-6Al-4V sheet metal joint is shown in figure 12. The 3003 aluminum braze alloy, which was placed adjacent to the edge of the faying surface, is shown to have penetrated completely into the weld nugget and filled the faying surface gap. Metallurgical reaction between the Ti-6Al-4V titanium base metal and the 3003 aluminum braze alloy is shown to be minimal. Examination of the fracture surfaces of the joints from specimens tested in reference 2 and the panels tested herein showed that the joints did not fail at the braze/Ti-6Al-4V titanium interface but were indicative of a ductile failure of both the braze and weld nugget.

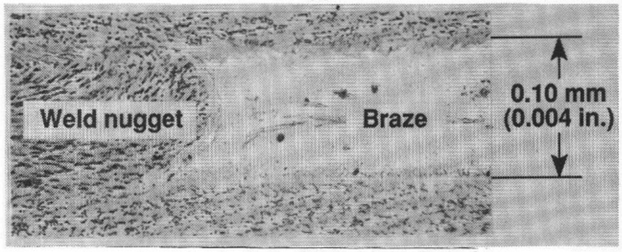


Figure 12. - Weld nugget - braze interface in a weldbrazed titanium skin-stiffener panel.

II. Brazed Bsc/Al Titanium Honeycomb-Core YF-12 Panels

Panel Test Results

The shear test results for the brazed Bsc/Al titanium honeycomb-core sandwich panels are shown in figure 13. All of the panels exceeded the design ultimate shear strength at both room temperature and 533 K (500°F). For the design verification panels tested at room temperature, the as-fabricated panel failed at a load corresponding to 125 percent of design ultimate shear strength and the panel exposed for 100 hours at 533 K (500°F) failed at 103 percent. For the panels tested at 533 K (500°F), the as-fabricated panel failed at 173 percent of design ultimate at this temperature and the exposed panel failed at 147 percent. The Bsc/Al face sheets for the panels exposed prior to testing were obtained from a different material supplier and exhibited lower shear strength properties than the face sheets used in the as-fabricated panels. Thus the difference in panel properties were attributed to variations in the properties of the face sheet material rather than the effects of exposure.

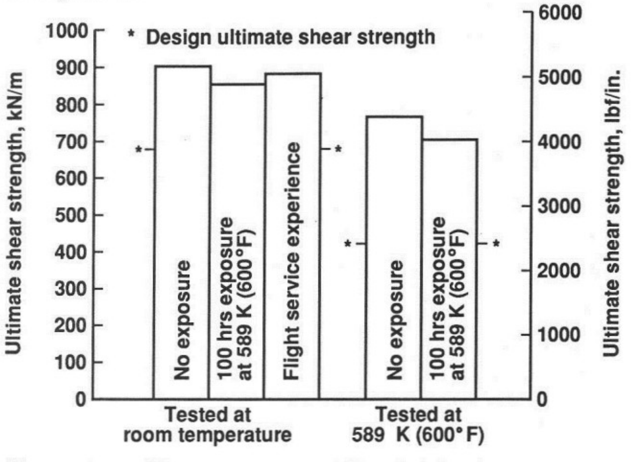


Figure 13. - Shear strength of Borsic/aluminum honeycomb-core sandwich panels.

The weight of the brazed Bsc/Al titanium honeycomb-core panel was 2.77 kg (6.1 lb) which was approximately 30 percent less than the original YF-12 wing panel it was designed to replace. This significant increase in structural efficiency is attractive for reducing the weight of airframe structures but the cost per unit mass of the Bsc/Al is approximately 10 times that of titanium sheet. Therefore the value of the weight reduction to both acquisition and life cycle costs must be carefully considered.

The panel subjected to flight service evaluation on the YF-12 airplane accumulated a total flight time of approximately 31 hours prior to testing. The total flight time spent at air speeds above Mach 2.6 was approximately nine hours and approximately four hours were spent at Mach 3.0. This panel failed at 103 percent of the shear design ultimate at room temperature. These results demonstrated that brazed Bsc/Al titanium honeycomb-core panels could be used to meet the primary structural requirements of supersonic aircraft.

Metallurgical Analysis

The major problem encountered in the initial attempts to braze Bsc/Al to itself or to titanium using 4047 aluminum braze alloy was interaction of the braze alloy with the composite which significantly degraded the properties of the material. As a result, the concept of using a material other than 6061 on the surface of the composite exposed to interaction with the braze alloy was devised (ref 12). The success of this approach is shown with the photomicrographs in figure 14 .

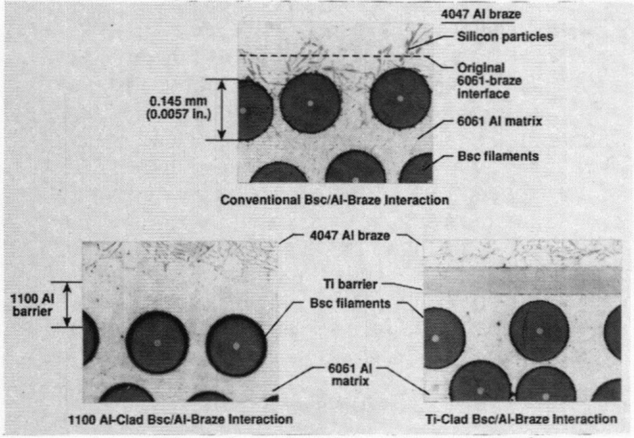


Figure 14. - Alleviation of metal matrix composite - braze interaction in a Borsic/aluminum honeycomb-core sandwich panel.

The three Bsc/Al samples used for the photomicrographs consisted of one conventional Bsc/Al specimen which had a bare surface of 6061 aluminum, one Bsc/Al specimen which had a layer of 1100 aluminum which replaced the outer layer of 6061 aluminum on the preconsolidated composite sheet, and one Bsc/Al sample on which a layer of commercially pure (CP) titanium was clad or diffusion bonded to the 6061 aluminum surface. The specimens were first chemically cleaned and a strip of 4047 aluminum braze alloy was placed on the surfaces of each of the specimens. They were then heated in vacuum at a pressure of 1.33 mPa (10^{-5} torr) to the desired brazing temperature of 864 K (1090°F) and held at temperature for 10 minutes to assure melting and flow of the braze. As shown in the upper portion of figure 14 , exposure of the molten braze alloy on the bare 6061 aluminum surface of the Bsc/Al specimen resulted in diffusion of the silicon from the braze alloy into the 6061 matrix to a depth below that of the first layer of borsic filaments. However, when the composite was altered by cladding the surface with either a layer of 1100 aluminum or CP titanium (as shown in the lower photomicrographs), diffusion of the silicon from the braze into the composite was restricted or eliminated.

Tensile testing of these materials following exposure to molten braze showed that both diffusion barrier concepts were successful in avoiding degradation of the mechanical properties of the as-consolidated Bsc/Al. As a result, all of the Bsc/Al materials used to fabricate the YF-12 panels were procured having a 0.13 mm (0.005 in) layer of 1100 aluminum on one surface.

III. Enhanced Diffusion Bonded Structural Elements

Structural Element Test Results

Figure 15 compares the face sheet stress-strain behavior of two EWC specimens tested at room temperature and 811 K (1000°F) with the stress-strain behavior of 0.51 mm (0.020 in) thick Ti-14Al-21Nb sheet exposed to simulated EDB processing conditions tested in uniaxial tension. The EWC strength of the Ti-14Al-21Nb sheet was 604.7 MPa (87.7 ksi) at room temperature and 410.3 MPa (59.5 ksi) at 811 K (1000°F). The uniaxial tensile yield strength of the Ti-14Al-21Nb sheet was 569 MPa (82.5 ksi) at room temperature and 386 MPa (56 ksi) at 811 K (1000°F). Thus, at both temperatures, the EWC strength exceeded the uniaxial yield strength of the Ti-14Al-21Nb sheet. This was the trend for all the EDB specimens that were tested. These results show that the EDB honeycomb core sandwich structure with 0.51 mm (0.020 in) thick face sheets can be stabilized beyond face sheet yield strength. In addition, the load index of all specimens tested at room temperature exceeded the target of 525 kN/m (3000 lb/in). The high load index values and the ability of the EWC specimens to sustain stresses greater than the tensile yield of the face sheets indicate the potential of the EDB fabrication methodology for this structural concept.

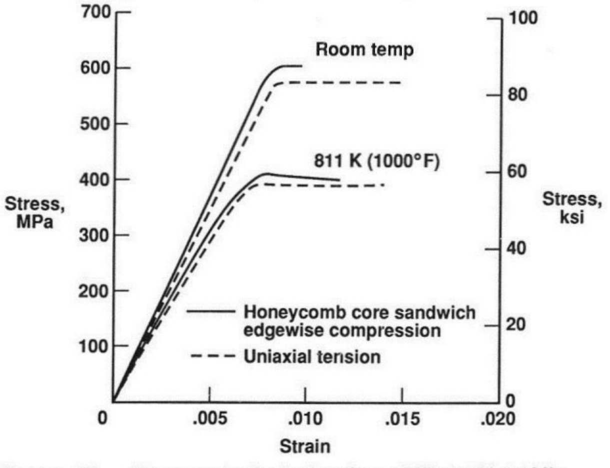
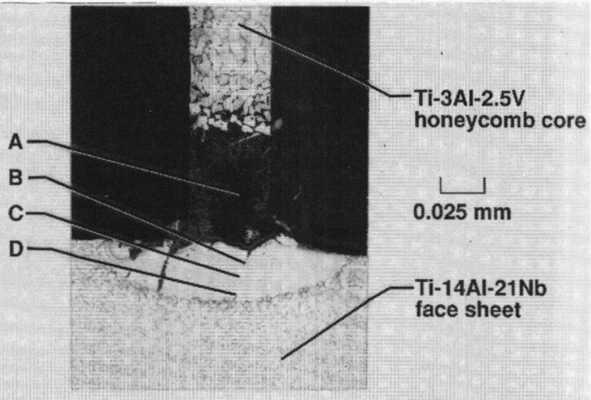


Figure 15. - Stress-strain behavior of Ti-14Al-21Nb sheet.

Using this selective removal of maskant/plating technique, panels were fabricated without edge close-outs with a mass as low as 0.5 lb/ft^2 for 0.178 mm (0.007 in) thick face sheets. Based on the mass of the face sheets and core, the weight contribution of the EDB material was less than 1 percent of the total panel mass.

Metallurgical Analysis

A photomicrograph of a joint segment from an EDB honeycomb-core sandwich panel is shown in figure 16 . As shown in the figure, the process was successful in limiting the metallurgical interaction effects between the titanium-base materials and the intermediate copper EDB material. The process resulted in a very small fillet at the joint interface and no unreacted copper in the fillet region. In addition, reaction or diffusion effects of the eutectic liquid were limited to a small region of the face sheet and core. No erosion occurred at the joint interface and limited phase transformation occurred within the honeycomb core. The x-ray chemical analysis of the joint showed that the bonding parameters fully diffused the intermediate copper material into the face sheet and core to very low concentration levels. This chemical analysis suggests that the joint has a higher remelt temperature than that used for bonding. In addition, results from tensile coupon tests of the Ti-14Al-21Nb face sheet material exposed to simulated EDB processing conditions indicated that EDB did not degrade the properties of the material (ref 10). In fact, EDB actually led to improvements in strength and ductility of Ti-14Al-21Nb, as compared to the properties of unprocessed sheet. This photomicrograph and the tensile test results show that localized application of intermediate copper material using the tank plating technique with the selective removal of maskant minimized both the weight penalty and the interaction effects associated with the intermediate copper material.



Bonding parameters: 1200 K, 20 min.
Ni flash, 0.076 mm Cu

Additional diffusion treatment: 1200 K, 60 min.

Component	Weight percentage			
	A	B	C	D
Ti	76	71	70	66
Al	4	5	5	6
Nb	5	11	14	18
Cu	15	13	11	10

Figure 16. - X-ray chemical analysis of Enhanced Diffusion Bonded face sheet - honeycomb core joint interface.

CONCLUDING REMARKS

An overview of the development of advanced fabrication processes to provide for the efficient incorporation of titanium and Bsc/Al metal-matrix composite into lightweight structural concepts for application of future supersonic and hypersonic aircraft has been presented. Based on the results presented, the following concluding remarks can be made:

Weldbrazing of Ti-6Al-4V Titanium Alloy

1. Weldbrazing was shown to be a process for joining Ti-6Al-4V titanium alloy sheet that combines resistance spotwelding and brazing to produce a hermetically sealed, sound metallurgical joint.
2. Flight qualification testing of weldbrazed Ti-6Al-4V skin-stiffened panels designed to meet the requirements of an upper wing panel on the Mach-3 NASA YF-12 airplane demonstrated that the shear strengths of the panels exceeded design requirements at both ambient temperature and 589 K (600°F).
3. One panel was proof loaded and subjected to flight service on the airplane and subsequently tested to failure at ambient temperature with no indication of detrimental effects.
4. Cost estimates indicated that the weldbrazing process resulted in a 15-20 percent cost savings compared to the costs of machining the original panel from thick plate.
5. Based on these results weldbrazing is considered to be a cost effective process suitable for fabricating Ti-6Al-4V titanium alloy primary structure for future supersonic cruise aircraft.

Brazing of Bsc/Al

1. Successful development of a brazing process for fabricating Bsc/Al titanium honeycomb-core structure was dependent on the use of an 1100 aluminum alloy diffusion barrier on the surface of the Bsc/Al exposed to the molten braze alloy during fabrication to avoid severe degradation of the composite material.
2. Degradation in the properties of the Bsc/Al due to thermal exposure during brazing was minimized by the development of a lightweight tooling concept which provided for a short duration braze cycle.
3. Successful development of a brazing process for fabricating the YF-12 panels consisted of two separate brazing cycles. The first braze cycle involved brazing of the titanium honeycomb core to the titanium edge members using 3003 aluminum braze alloy. The second braze cycle consisted of brazing the Bsc/Al face sheets to the titanium core/frame

subassembly using 4047 aluminum braze alloy.

4. The mass of the brazed Bsc/Al panels was approximately 30 percent less than the mass of the original wing panels for the airplane indicating a large potential for weight reduction on future airframes.

5. Shear test results of all of the full-scale panels exceeded the design requirements of the aircraft. Also shear test results of a panel following flight service evaluation at air speeds up to Mach 3 exceeded the shear ultimate requirements.

6. Based on these results, the brazing process for fabricating Bsc/Al titanium honeycomb-core sandwich structure is considered suitable for primary structural applications on future supersonic aircraft.

Enhanced Diffusion bonding

1. A joining process (designated Enhanced Diffusion Bonding) for fabricating lightweight, high-temperature honeycomb-core sandwich panels using commercially available titanium aluminide face sheets was developed.

2. Enhanced Diffusion Bonded structural elements having Ti-14Al-21Nb face sheets and Ti-3Al-2.5V honeycomb core were fabricated without edge close-outs having a mass as low as 0.5 lb/ft^2.

3. The application of electroplated EDB material only on the edges of the honeycomb core minimized metallurgical interaction effects.

4. Isothermal eutectic formation and subsequent isothermal solidification due to metallurgical reaction between the EDB material and the face sheet/core components resulted in the composition of the joint having a higher remelt temperature than that used for bonding.

5. Edgewise compression testing of the EDB titanium aluminide sandwich specimens showed that at maximum load the stresses developed in the Ti-14Al-21Nb face sheets exceeded the yield strength of the material.

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