Brazing Titanium for Structural and Vehicle Applications

The effects of hot isostatic pressing and process changes on the properties of vacuum-brazed titanium were investigated

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Titanium is a strong candidate to be used as a structural material for all new Army ground vehicles, due to its high specific strength, excellent corrosion resistance, and inherent ballistic resistance. However, the use of titanium as a structural material is a much less mature technology than both steel and aluminum alloys, especially in the area of joining. While welding is the typical joining method for titanium, vacuum brazing is an option in areas that are difficult to access for welding as well as areas near other nonmetallic materials, such as ceramics. This study was undertaken to investigate processes that would be more expeditious and less costly than welding plus hot isostatic pressing.

This work focuses on vacuum brazing of both Ti-6Al-4V and commercially pure (CP) Grade 4 titanium. The effect of processing changes (alloy, temperature, pressure), including postbraze hot isostatic press (HIP) processing, on mechanical properties and microstructure are discussed. This study examines the joining of both plate materials as well as lightweight periodic pyramidal core structures. Shear and tensile testing was performed to determine the strength/ductility relationship to the various processing routes. Microscopy (optical and SEM) was employed to quantify the degree of metallic bonding and to examine microstructural changes, both within the base materials and at the braze interface, associated with the process variations.

In this study, plate material was adequately joined with moderate strength and ductility via braze plus hot isostatic pressing (HIP) and diffusion bonding (DB) plus HIP processing methods. Although brazing alone did not result in sufficient metallic bonding for the replacement of electron beam welding plus hot isostatic pressing, it did provide sufficient bonding for the pyramidal core sandwich plates. For these types of structures, metallic bonding at the core-to-facesheet interface is critical to overall system performance.

Reducing Size and Weight

The desire for smaller, lighter Army vehicles has motivated an increased need for both lightweight metallic and ceramic materials. Advanced ceramics are promising materials because of their high hardness and elastic modulus. However, to fully achieve the potential of ceramics, they must be incorporated into the proper system. The ability to incorporate both ceramics and lightweight metals into an advanced structure allows the hard, but brittle ceramics to be used in survivable structures in aggressive environments. In this study, the joining of monolithic titanium was investigated to determine if brazing or brazing plus hot isostatic pressing could replace electron beam welding (EBW) plus hot isostatic pressing in the process of using a ceramic within a titanium structure.

In addition to the process of joining titanium in the vicinity of ceramics, low-density sandwich plates are also of interest for ground vehicles. The ability to adequately join facesheets with a low-density core is important to the integration of sandwich structures into multifunctional systems. In general, titanium core topologies include honeycomb, open and closed celled foams, and periodic truss geometries, to name a few. In the form of sandwich panels, all core topologies exhibit improved energy-absorbing capabilities over equivalent weight monolithic plates. This property makes titanium sandwich panels an important technology for weight-critical defense applications.

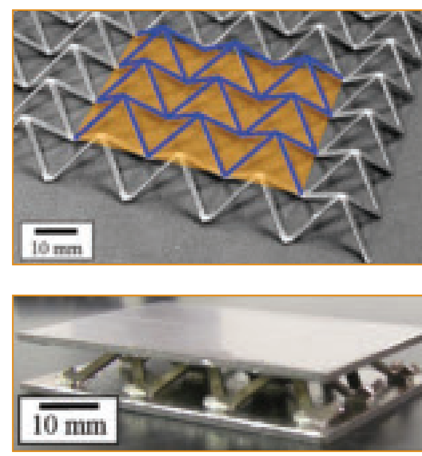

Fig. 1 — Examples of the geometry of titanium pyramidal core with and without brazed facesheets.

The development of a steel periodic pyramidal core topology has been outlined by Sypeck and Wadley (Ref. 1). The manufacturing and bonding processes are clearly outlined for both stainless and low-carbon steel sandwich panels. More recently, work done by Tice and Zupan (Ref. 2) has focused on manufacturing titanium pyramidal core sandwich panels to take advantage of titanium's superior specific strength and stiffness vs. steel.

Historically, Ticuni™ braze foil has

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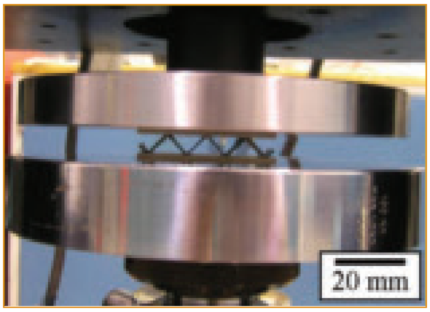

Fig. 2 — Test configuration for uniaxial flatwise compression.

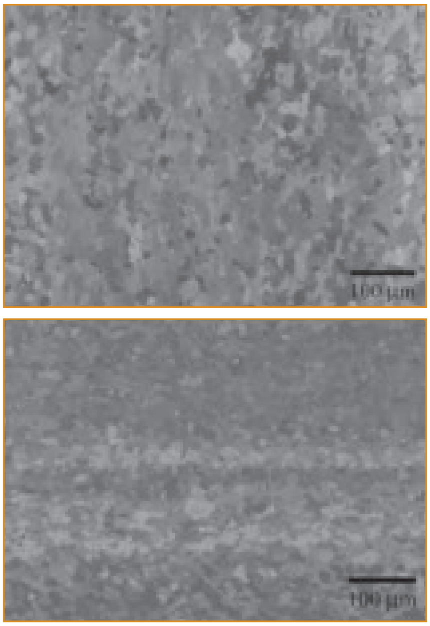

Fig. 3 — Low-magnification images of monolithic Ti-6Al-4V (top) and an interface resulting from Weld+HIP (bottom).

been shown to provide braze joints with increased strength and service temperature capabilities vs. silver-copper alloys (Refs. 3, 4). Although Ticuni™ provides increased strength and service temperature, its melting temperature is near the recrystallization temperature of titanium. Thus, during brazing, the base material may undergo a phase transformation, resulting in a degradation of base material properties.

A study conducted by Ko, et al., outlined the joining of Ti-6Al-4V and CP titanium with various zirconium-rich braze alloys (Ref. 5). They found that these alloys could be joined at 880°–900°C, such that the resulting tension specimens would fail in the base material. Although monolithic materials can be joined with high-temperature alloys like Ticuni™, low-density sandwich plates require reduced temperature and pressure during thermal processing. Thus, a zirconium-rich braze alloy (BRAZ1954) was targeted for the sandwich panel application. The braze alloys considered for this study are presented in Table 1.

Table 1 — Braze Alloys Used in this Study Include Ticuni™ (WESGO Metals, Morgan Advanced Ceramics) and BRAZ1954 (Arris International)

Name	Composition (Wt-%)	Form	Liquidus (°C)
Ticuni™	Ti-15Cu-15Ni	Foil	960
BRAZ1954	Ti-37.5Zr-15Cu-10Ni	Paste Tape	835

This work focuses on vacuum brazing of titanium and the effect of processing changes (alloy, temperature, pressure) and postbraze hot isostatic pressing (HIP) on mechanical properties and microstructure. This report examines the joining of standard Ti-6Al-4V plate structures as well as sandwich plates consisting of CP titanium facesheets joined to a CP titanium pyramidal core. Different braze alloys and forms are introduced and evaluated based on strength, thermal cycle, and ease of application.

Details of Joining Methods

In order to characterize different methods for joining monolithic titanium structures when ceramic components are nearby, four different bonding conditions were used to join 75- × 75- × 50-mm blocks of titanium (Ti-6Al-4V, AMS-T-9046A AB-1). The first method (Weld+HIP) was a gas tungsten arc (GTA) weld around the exterior of the Ti-6Al-4V blocks, followed by hot isostatic pressing at 900°C for 2 h (with a stress anneal at 593°C for 1 h) at 103 MPa in argon. The second method (DB+HIP) was a diffusion bonding step at 1000°C for 10 min in vacuum under ~15 kPa of deadweight using a 50-µm layer of active braze (Ticuni™) around the edge of the Ti-6Al-4V blocks followed by the HIP process described in the first method. The third method (Braze+HIP) used the same active braze cycle as in the second method (Ticuni™, 1000°C for 10 min in vacuum) followed by the HIP process; however, the 50-µm active braze foil was placed over the entire Ti-6Al-4V bonding surface prior to heating. The fourth method (Braze only) was similar to the third method except there was no post-HIP cycle following the active brazing step (Ticuni™, 1000°C for 10 min in vacuum). As a baseline, a monolithic Ti-6Al-4V block (75 × 75 × 100 mm) was also included in the HIP cycle.

Tensile bars were electrical-discharge-machine (EDM) cut out of the monolithic and joined Ti-6Al-4V blocks according to the ASTM E8 (size TR 3A). All tests were run at 3 mm/min, and a minimum of five tensile bars per joining method were tested. Optical microscopy was used to determine the degree of bonding and to ascertain the effect of the processing parameters on the microstructure at the joining interface.

Verifying the Vacuum Brazing Process

In order to verify the application of vacuum brazing as a viable method for joining titanium pyramidal core sandwich structures, some consideration of the thermal processing parameters for each braze alloy needed to be addressed. Since the structures considered in this study were low-density, CP titanium cores (Fig. 1), they were extremely susceptible to creep deformation during thermal treatment. Preliminary results demonstrated that these structures could not resist creep for the standard Ticuni™ braze temperatures. Therefore, BRAZ1954 was chosen as the primary braze alloy for these structures due to its reduced time, temperature, and pressure requirements vs. its Ticuni™ counterpart.

Since there was no literature on joining creep-sensitive, low-density sandwich plates with BRAZ1954, a small survey of thermal processing parameters was conducted. Each proposed thermal treatment was characterized via double-lap shear testing (ASTM D 3528). Specimens were made via four different thermal cycles in order to determine a favorable set of braze parameters for maximizing joint strength for these structures. All samples were placed under 50 kPa of deadweight pressure during brazing. In addition, vacuum was kept at a minimum of 10^{-5} torr throughout the entire thermal treatment. The targeted thermal cycles for this study were as follows: T = 890°C for t = 10 min, T = 900°C for t =

Table 2 — Average Strength and Ductility Results

Process	σ_y (MPa)	σ_{uts} (MPa)	Elongation (%)
Monolithic	870.4 (13.7)	913.3 (19.4)	16.1 (2.7)
Weld+HIP	830.0 (11.0)	906.4 (15.8)	9.1 (2.8)
DB+HIP	754.1 (12.9)	848.5 (13.7)	13.8 (2.4)
Base+HIP	761.0 (8.2)	852.5 (4.7)	11.6 (3.2)
Braze only	751.1 (53.4)	806.7 (136.7)	3.1 (5.4)

Note: Average strength and ductility results are reported for monolithic Ti-6Al-4V joining.The values in parentheseis indicate standard deviations.

10 min, T = 900°C for t = 20 min, and T = 900°C for t = 10 min followed by a HIP cycle as described previously. All specimens were tested in uniaxial tension and the resulting shear strength of the braze material was determined for each set of braze parameters. Once the best thermal processing parameters were determined, standard tensile specimens were subjected to an identical thermal treatment and subsequently tested in the as-received and as-processed conditions (ASTM E 8). From these experiments, some degradation in base material properties was observed due to thermal processing.

Verifying the Braze Alloy

In order to verify that BRAZ1954 could be used to join pyramidal core sandwich plates, individual sandwich test specimens were manufactured and tested. Each test specimen consisted of Grade 4 commercially pure titanium (AMS-T-9046A CP-1) facesheets braze joined to CP titanium pyramidal core using the set of favorable thermal processing parameters as determined from the double-lap shear testing. For all sandwich specimens tested in this study, the pyramidal core was fabricated from 0.61-mm-thick CP Grade 4 sheets, resulting in a geometry as defined in Fig. 1, whereas the facesheets were cut from 1.22-mm-thick CP Grade 4. The core used in this study has a relative density of 4% as compared to a monolithic plate of equivalent volume. All test panels contain a minimum of 4 unit cells, resulting in a minimum of 9 contact points on the bottom facesheet, and 6 contact points on the top facesheet. Prior to brazing, all parts underwent a surface treatment to remove surface oxidation. The surface treatment included a 5-min grit blast, pressurized nitrogen gas rinse, and a 30-min ultrasonic ethanol bath. A single sheet of a zirconium-rich titanium braze tape (BRAZ1954) was applied to each facesheet using a steel roller, prior to stacking the core into the sandwich panel configuration. Finally, the facesheet and core components were joined via the favorable set of thermal processing parameters as determined by the double-lap shear testing described previously. Sandwich test specimens were tested in quasi-static out-of-plane compression as shown in Fig. 2.

Experiment Results

The results from the tensile testing of the joined titanium blocks are presented in Table 2. The strengths and elongations listed are the average values with the corresponding standard deviations also presented. The Weld+HIP and Braze only specimens all failed at the braze interface, while the DB+HIP and Braze+HIP specimens predominately failed away from the braze interface. This phenomenon resulted in lower yield strengths for the DB+HIP and Braze+HIP specimens (vs. Weld+HIP), but modestly improved elongation. The strength and elongation values for the Braze-only specimens were lower and significantly more inconsistent than the other joining techniques as indicated in Table 2.

Optical micrographs of the monolithic titanium and the Weld+HIP structures are presented in Fig. 3. Both images show a similar fine, equiaxed grain structure with a grain size on the order of 10–20 μm. The interface in the Weld+HIP image is evident, but the grains do not look noticeably different than the rest of the structure.

Higher-magnification optical micrographs of the DB+HIP and Braze+HIP are presented in Fig. 4. Both images show a more coarsened structure (grain size ~100 μm) than in Fig. 3. Again the interface is evident in both structures; however, the Braze+HIP contains the coarse-grained braze material (grain size ~200 μm) covering the entire interface. In all cases (except Braze only), the microstructures were homogeneous throughout the titanium bulk and along the joining interface.

Fig. 4 — High-magnification images of a Ti-6Al-4V interface resulting from DB+HIP (top) and Braze+HIP (bottom).

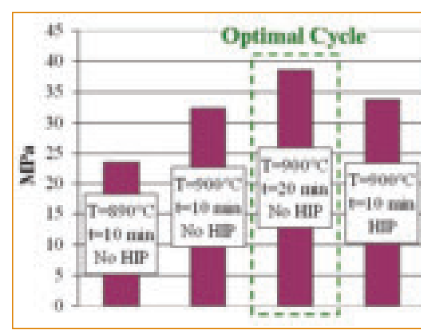

Fig. 5 — Double-lap shear strength results for CP titanium brazed with BRAZ1954 for the described thermal cycles.

The average shear strength of the BRAZ1954 can be viewed in Fig. 5 for the various thermal cycles employed in this study. Strength and ductility were consistent for both tape and paste forms. In addition, failure occurred entirely in the braze material for all specimens, indicating that the surface treatment was sufficient. Examination of the specimens revealed that failure in the braze layer was primarily brittle in nature.

The subsequent tensile true stress-strain plots for the base material, CP titanium, can be viewed in Fig. 6. Prior to thermal treatment, yield strength and percent elongation were measured and

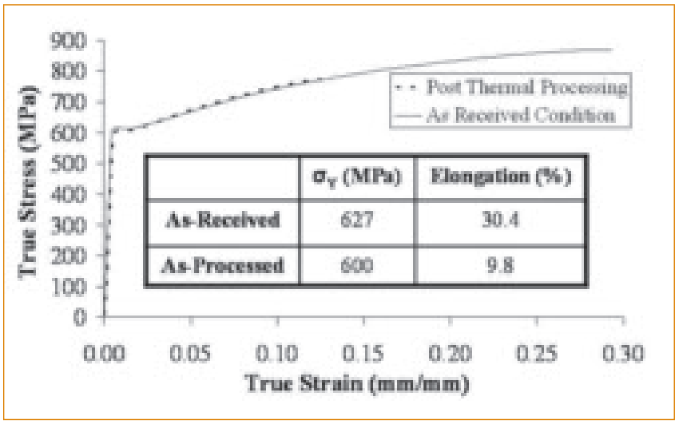

Fig. 6 — True tensile stress-strain response for as-received and as-processed CP titanium (0.610-mm-thick sheet perpendicular to the rolling direction).

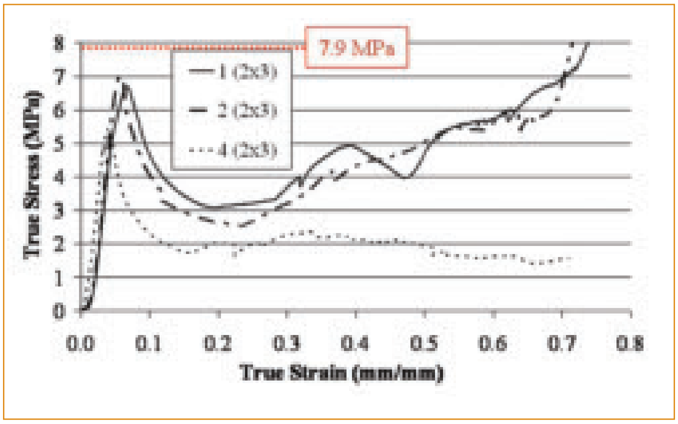

Fig. 7 — Compressive stress-strain response for pyramidal core sandwich plates (brittle joint failure).

were 627 MPa and 30.4%, respectively. After the base material underwent the optimal braze cycle, yield strength and percent elongation were measured and were 600 MPa and 9.8%, respectively. Thus, some degradation in base material properties occurred during joining of the structure.

The resulting compressive stress-strain plots for the sandwich panel specimens can be viewed in Figs. 7 and 8. Peak compressive strength ranged from 5.4 to 7.8 MPa, with an average peak strength of 6.9 MPa and a standard deviation of 0.23 MPa. Analytical modeling for this geometry predicted a peak strength of 7.9 MPa based on Euler buckling of the individual struts within the core (Ref. 2). Inspection of these panels revealed that for some panels, failure occurred due to elastic buckling of the struts, whereas for other panels, failure occurred due to brittle fracture at the joints, or debonding of the facesheets.

Evaluation of Joining Methods

The section of this study that targeted joining monolithic titanium was successful in determining the validity of replacing an electron beam welding plus hot isostatic pressing (EBW+HIP) process in the course of joining titanium in the vicinity of ceramics. Testing of the different joining methods highlighted some definite candidates for the replacement of the EBW+HIP process, such as the Weld+HIP, and demonstrated the need for optimization in certain processes (DB+HIP and Braze+HIP) to obtain viable replacements.

The Braze-only method was the least successful joining option that would require the most development before a plausible solution could be realized. The HIP procedure was verified as a current necessary step to get adequate interface properties. The HIP procedure (900°C, 2 h) did not diminish the base Ti-6Al-4V properties (the strength/ductility properties are still within the specification), and did not measurably alter the base material microstructure.

The Weld+HIP procedure showed the highest strength/ductility combination of the joining methods. The joint strength properties only trail the monolithic material by ~5%, but there is a significant reduction in ductility (more than 40%). However, 9% ductility is an acceptable measure for a joined structure. The material failure was consistently at the joint interface indicating little effect of the thermal treatment on the base material. Keeping the thermal treatment temperature near or below the beta transus is a necessary step for this application.

Both DB+HIP and Braze+HIP procedures achieved good metallic bonding between the base titanium plates while attaining approximately the same level of mechanical properties in their final joints. The DB+HIP treatment demonstrated a microstructure with clean grain boundaries and homogeneous bonding along the entire interface. The Braze+HIP treatment produced acceptable braze homogeneity along the entire boundary with little visible porosity. Both sets of tensile samples failed predominately away from the joint interface (within the base metal), which was subjected to the same thermal treatment. The high-temperature braze or diffusion bond cycle (1000°C for 10 min) was significant enough to lower the yield strength ~13%, while decreasing the ductility 15–20%. Since this thermal cycle was above the beta transus, it caused unwanted grain growth and weakened the base structure.

In their current maturity, either option would be functional; however, their performances are not ideal for titanium joining in vehicle or structural applications. However, the DB+HIP or the Braze+HIP process should be feasible options with minor modifications. A reduction in the diffusion bonding temperature should induce less of an effect on the base titanium, while still allowing for adequate bonding between the titanium plates. While a reduction in the brazing temperature for Ticuni™ could minimize some of the grain growth, there is not much room for reduction because of the high liquidus temperature (960°C). A transition to an alternative, lower temperature braze material (such as BRAZ1954) is a more reasonable option that should allow a Braze+HIP type procedure to successfully be implemented for titanium joining near ceramics.

The Braze-only treatment was the least successful in creating a good metallic bond between the titanium plates. The yield strength of the Braze-only joint was reduced by ~13% and the ductility was reduced a remarkable 80%. In addition, the strength and ductility numbers were extremely inconsistent. The standard deviations were at least twice as much as the other joining conditions. All of these findings can be directly related to the limited pressure (~15 kPa) applied to the titanium structure during brazing. This led to limited braze flow, poor wetting, and increased porosity at the braze inter-

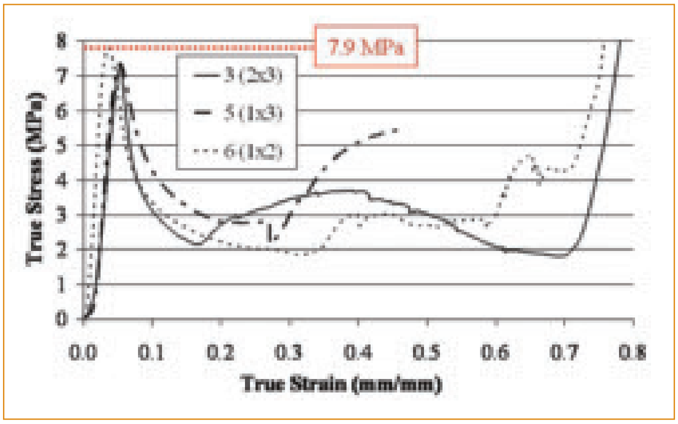

Fig. 8 — Compressive stress-strain response for pyramidal core sandwich plates (elastic strut failure).

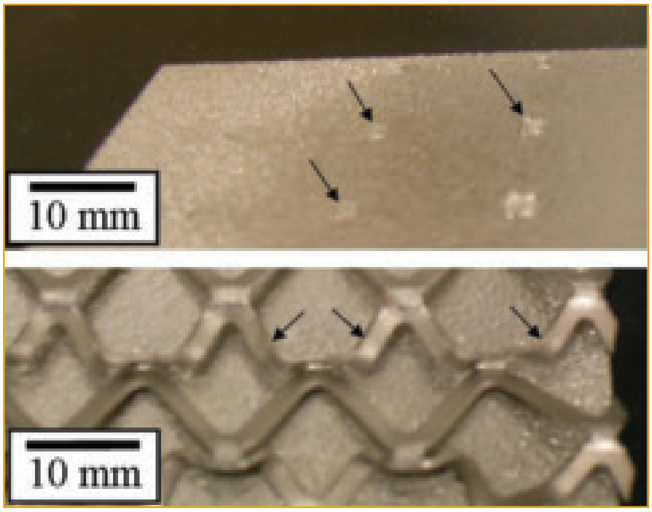

Fig. 9 — Fully compressed samples indicate that both joint failure (top) and strut failure (bottom) were primary failure modes for pyramidal core in this study.

face. A significant increase in bonding pressure during brazing should improve braze flow and enhance wetting, thereby enabling a marked improvement in bond strength and ductility. With an optimized time/temperature/pressure schedule and a lower temperature brazing alloy, a Braze-only procedure may function without a post-HIP cycle.

Double-lap shear specimens joined with the BRAZ1954 alloy revealed a much lower shear strength for all thermal cycles implemented than that reported by Ko and colleagues (Ref. 5). Since similar thermal cycles were used in both studies, the only parameter that differed significantly was pressure on the sample during brazing. Since the titanium structures in this study could not resist creep under high pressure during brazing, only 50 kPa of deadweight pressure was applied. Ko and colleagues applied approximately 1 MPa during brazing. This pressure difference is identified as the primary reason for the low shear strength values reported here. Increased pressure during brazing promotes flow and reactivity of the braze material, thus decreasing the number of voids in the resulting braze layer. Further studies hope to use Incusil-ABA™ as the possible joining method for these structures. Since Incusil-ABA™ has a much lower braze temperature than BRAZ1954, the structure would be less susceptible to creep under increased pressure during brazing. This may allow for improved joint strength.

When examining the effect of thermal cycle parameters on the shear strength of the double-lap shear specimens, some interesting results should be noted. First, an increase of 10°C in braze temperature resulted in a 37.4% increase in shear strength. Second, doubling the braze time from 10 min to 20 min (at 900°C) resulted in an additional 19.5% increase in shear strength. These two factors indicate that braze strength must be related to the braze layer's ability to react chemically with the base material. Finally, adding a postbrazing HIP cycle did not result in any significant increase in braze strength for these structures, indicating that voids in the braze layer are not the limiting flaw as previously proposed. Perhaps pressure during brazing contributes significantly to the braze layer's ability to form chemical bonds with the base material. This is consistent with diffusion bonding of titanium.

For the optimal BRAZ1954 thermal cycle, the base material properties show a degradation of yield strength of 4.3% and a reduction in ductility represented by a decrease in percent elongation of 67.8% from that of the as-received condition. Although the strength of the base material was conserved during thermal processing, the ductility of the base material deteriorated significantly. For pyramidal core sandwich structures, peak compressive strength is only dependent on base material yield strength for an optimized structure, because failure should occur entirely due to elastic/plastic buckling of the struts (Ref. 2). Therefore, the decreased ductility in the base material due to thermal processing is not significant to the performance of the structure. The degradation of yield strength is a much more critical factor to consider, because it is directly correlated to peak strength, assuming sufficient bonding. Perhaps the use of Incusil-ABA™ to join these structures will result in zero change in base material yield strength due to a significantly lower braze temperature.

Compression tests of the CP titanium pyramidal core sandwich structures revealed a strong dependence of peak compressive strength of the core on the ability to bond the core and facesheets. Since pyramidal core structures are stretch-governed in nature, they require that the work energy during deformation be dissipated by compressive and tensile stretching of the struts and facesheets (Ref.2). Therefore, an adequate bond at each joint interface must be achieved such that microstretching of the facesheets is initiated, and failure occurs due to elastic/plastic buckling of the struts.

For the samples tested in this study, peak strength and panel failure mechanism could be directly correlated through posttest inspection of the test samples. For specimens 1, 2, and 4 (Fig. 5), joint failure resulted in a reduction of peak strength because the joints failed before the potential strength of the individual struts could be fully realized. However, for specimens 3, 5, and 6 (Fig. 6), joint strength was adequate such that subsequent buckling of the struts initiated failure. These two different failure mechanisms are exemplified in Fig. 9.

Since all test specimens were cut from a single sandwich panel, it was determined that thermal gradients near the edge of the panel during the cooling portion of the braze thermal cycle produced

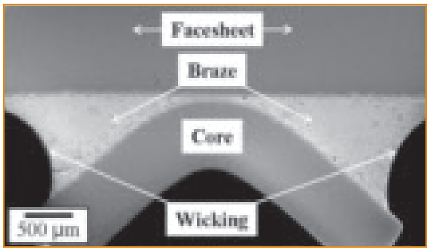

Fig. 10 — BRAZ1954 provides intimate joining at both the facesheet and core interfaces for the favorable set of thermal processing parameters presented in this study.

lower joint strength for some of the test samples. This would explain why some test samples exhibited much higher peak compressive strength than other samples in the study. In later studies, this problem was corrected by surrounding the large sandwich panels by bulk material during brazing, such that the entire sandwich panel cooled at the same rate. Samples tested using this method closely matched the analytical model (Ref. 2). Figure 10 displays an example of the type of metallic bonding that can be achieved with the thermal process described in this study for BRAZ1954 if all of the proper precautions are taken. In this image, it is evident that the braze material fully wets both the facesheet and apex of the core. In addition, the braze wicked between the facesheet and core, thereby providing additional reinforcement against shear failure. Further microscopy may reveal chemical bonding at the facesheet-to-core interface due to diffusion of the braze elements into the base titanium.

Summary

• Braze+HIP and DB+HIP are both functional options for joining titanium structures in the vicinity of ceramics. While the braze and diffusion bonding parameters (time and temperature) were not optimized, the final mechanical properties were adequate. Decreasing the diffusion bonding or brazing temperature should minimize grain growth, and improve both the strength and ductility of the structure.

• The Braze-only joining condition was not successful in creating a viable structure. The poor metallic bonding is a direct result of low pressure applied to the system during brazing. Further work is needed to determine whether increased loading during thermal processing could improve bond strength and possibly eliminate the need for a HIP treatment.

• Titanium pyramidal core sandwich panel components can be successfully joined using BRAZ1954. While the shear strength measured was considerably lower than historical results, it is still high enough to invoke stretching of the core microstructure. Improvements in braze shear strength were produced by increasing both time and temperature during brazing; however, a post-HIP procedure was shown to have a negligible effect on shear strength. Ticuni™ is still an alternative for more dense structures; however, the elevated processing temperature minimizes the allowable pressure on the structure during brazing (to avoid creep deformation) and enables adverse changes in base material microstructure associated with heating over the beta transus.

• Different braze alloys (such as Incusil-ABA™) may provide similar or improved strength at lower braze temperatures, thus eliminating risks of creep deformation and degradation of base material properties. A reduced temperature brazing alloy with more pressure applied during brazing may provide a stronger metallic bond.

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