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Titanium Brazing for Structures and Survivability

by Kevin J. Doherty, Jason R. Tice, Steven T. Szewczyk, and Gary A. Gilde

ARL-RP-177 **May 2007**

A reprint from the *Proceedings of the 3rd International Brazing and Soldering Conference*, pp. 268–273, San Antonio, TX, 24–26 April 2006.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
May 2007	Reprint	August 2004–May 2005

4. TITLE AND SUBTITLE
Titanium Brazing for Structures and Survivability

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Kevin J. Doherty, Jason R. Tice, Steven T. Szewczyk, and Gary A. Gilde

5d. PROJECT NUMBER
622105.AH84

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-WM-MD
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-RP-177

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
A reprint from the *Proceedings of the 3rd International Brazing and Soldering Conference*, pp. 268–273, San Antonio, TX, 24–26 April 2006.

14. ABSTRACT
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This work focuses on vacuum brazing of titanium (both Ti-6Al-4V and commercially pure titanium) and the effect of processing changes (alloy, temperature, pressure), including post-braze hot isostatic pressing, on mechanical properties and microstructure. This study will examine the joining of both plate materials as well as lightweight, periodic pyramidal core structures. Shear and tensile testing is performed to determine the strength/ductility relationship to the various processing routes. Microscopy (optical and SEM) is employed to quantify the degree of bonding and to examine the microstructural changes, both within the base materials and at the bond line, associated with the process variations.

15. SUBJECT TERMS
titanium, brazing, structures, sandwich panels

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Kevin J. Doherty
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UL	12	**19b. TELEPHONE NUMBER** (*Include area code*)
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED			410-306-0871

Proceedings of the 3rd International Brazing and Soldering Conference, April 24–26, 2006, Crowne Plaza Riverwalk Hotel, San Antonio, Texas, USA

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Abstract

Titanium is a candidate as a structural material for all new tactical and armored ground vehicles, because of its high strength-to-weight ratio, excellent corrosion resistance, and inherent ballistic resistance. However, titanium as a structural material is much less mature 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 work focuses on vacuum brazing of titanium (both Ti-6Al-4V and commercially pure titanium) and the effect of processing changes (alloy, temperature, pressure), including post-braze hot isostatic pressing, on mechanical properties and microstructure. This study will examine the joining of both plate materials as well as lightweight, periodic pyramidal core structures. Shear and tensile testing is performed to determine the strength/ductility relationship to the various processing routes. Microscopy (optical and SEM) is employed to quantify the degree of bonding and to examine the microstructural changes, both within the base materials and at the bond line, associated with the process variations.

Introduction

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

The ability to adequately join facesheets with a low-density core is important in the application of titanium sandwich structures into multifunctional systems. In general, titanium core topologies include honeycomb, open and closed celled foams, and periodic truss configurations, to name a few. In the form of sandwich panels, all of these core topologies exhibit improved energy absorbing capabilities over equivalent weight monolithic plates. This property makes titanium sandwich panels an important technology for defense applications where weight efficiency is crucial to system performance.

The development of a steel periodic pyramidal core topology has been outlined by Sypeck and Wadley[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[2] has focused on manufacturing titanium pyramidal core sandwich panels due to titanium's inherent strength-to-weight advantage over steel.

Historically, Ticuni™ braze foil has been shown to provide braze joints with increased strength and service temperature capabilities over basic silver-copper alloys.[3,4] Although Ticuni™ braze alloy provides increased strength and service temperature over silver-based alloys, its melting temperature is near the recrystallization temperature of titanium. Thus, during brazing, the base material can undergo significant phase transformation, resulting in a degradation of material properties. A study conducted by Ko, Suzumura, and Onzawa, reported the joining of Ti-6Al-4V and CP titanium alloys with zirconium-rich braze alloys.[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. These results initiated the selection of a zirconium-rich braze alloy (BRAZ1954) and an even lower melting silver-based alloy (Incusil-ABA™) as candidates for this sandwich panel application. The braze alloys considered for this study are presented in Table I.

This work will focus on vacuum brazing of titanium and the effect of processing changes (alloy, temperature, pressure) and post-braze hot isostatic pressing on mechanical properties and microstructure. This report will examine both bonding of standard Ti-6Al-4V plate structures as well as weight efficient systems such as commercially pure (CP) titanium facesheets to a corresponding CP titanium pyramidal core. Different braze alloys and forms will be introduced and evaluated based on strength, thermal cycle, and ease of application.

Name	Wt. % Composition	Form	Liquidus (°C)
Ticuni™	70Ti-15Cu-15Ni	Foil	960
Incusil-ABA™	59Ag-27.25Cu-12.5In-1.25Ti	Foil	715
BRAZ1954	37.5Ti-37.5Zr-15Cu-10Ni	Paste Tape	835

Table I: Brazing alloys for consideration in this study. *Ticuni™ and Incusil-ABA™ are products of WESGO Metals, Morgan Advanced Ceramics. BRAZ1954 is a product of Arris International.

Experimental Procedures

Four different bonding conditions were used to join 75 mm x 75 mm x 50 mm blocks of titanium (Ti-6Al-4V, AMS-T-9046A AB-1) together. The first method (Weld+HIP) was a tungsten inert gas (TIG) weld around the exterior of the Ti-6Al-4V blocks followed by hot isostatic pressing (HIP) at 900ºC for 2 hours (with a stress anneal at 593ºC for 1 hour) at 103 MPa in argon. The second method (DB+HIP) was a diffusion bonding step at 1000ºC for 10 minutes in vacuum under ~15 kPa of deadweight using a 50 µm layer of active braze (Ticuni™, 70% Ti, 15% Cu, 15% Ni, Morgan Advanced Ceramics) 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™, 1000ºC/10 minutes 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 HIP cycle following the active brazing step (Ticuni™, 1000ºC/10 minutes in vacuum). As a baseline, a monolithic Ti-6Al-4V block (75 mm x 75 mm x 100 mm) was also included in the HIP cycle.

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

The application of vacuum brazing as a method of joining titanium pyramidal core sandwich structures required some consideration of the braze cycle parameters for each alloy. Since the structures considered in this study were low-density, CP titanium cores (Fig. 1), they were extremely susceptible to creep during thermal treatment. Ticuni™ braze foil was put on hold for this application based on its required braze temperature of ~1000°C. Preliminary results proved that these structures could not resist creep for any significant amount of time at that temperature. Therefore, BRAZ1954 was implemented as the primary braze alloy for these structures due to its increased strength over Incusil-ABA™ and its decreased time and temperature requirements over Ticuni™.

Commercially pure titanium (CP, AMS-T-9046A CP-1) facesheets were brazed to CP titanium pyramidal core structures. The pyramidal core structures were fabricated from CP sheets 0.61 mm thick with geometry defined in Fig. 1, while the facesheets were primarily 1.22 mm thick. This core has a relative density of 4% as compared to a monolithic plate of equivalent volume. All sandwich panels contain a minimum of 4 unit cells, resulting in a minimum of nine contact points on the bottom facesheet, and six contact points on the top facesheet. Prior to brazing, all samples underwent a surface treatment to remove oxides and ensure uniformity. The surface treatment included a 5 minute grit blast, pressurized nitrogen gas rinse, and a 30 minute ultrasonic cleaning in ethanol. A single sheet of a zirconium-rich titanium braze tape (BRAZ1954, Arris International) was applied to each facesheet using a steel roller, prior to stacking the core into the sandwich panel configuration. This configuration was placed in the vacuum furnace under 50 kPa of deadweight, and thermally treated at 900°C for 20 min. This braze cycle was determined to be optimal by the shear testing described below.

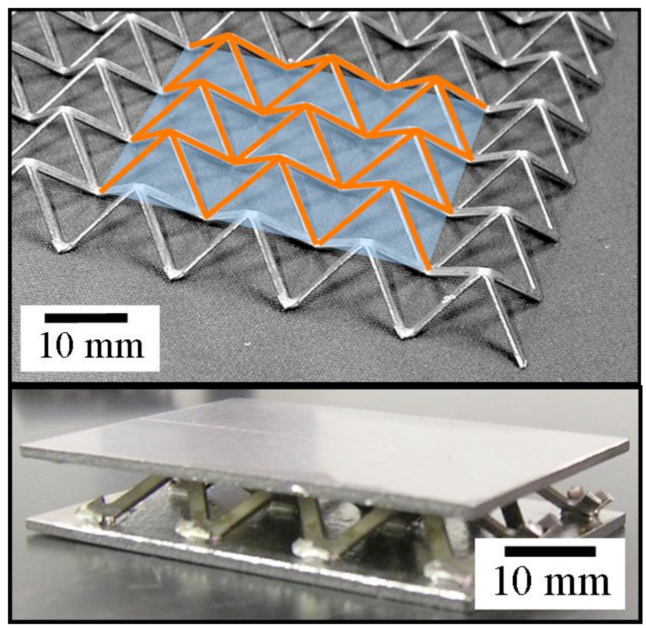

Figure 1: Examples of the geometry of titanium pyramidal core with and without brazed facesheets.

Both shear and compression tests were performed to verify the joint properties of the CP titanium sandwich panels brazed with BRAZ1954. Brazed facesheet/core configurations were tested in flatwise compression (ASTM C365). An example of this testing is shown in Fig. 2. Double-lap shear specimens were made via four different thermal cycles in order to determine the optimal braze parameters to maximize joint strength for these structures. All samples were placed under 50 kPa of deadweight during brazing. The thermal cycles were as follows: T=890°C for t=10 min, T=900°C for t=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. These specimens were tested in uniaxial tension and the resulting shear strength of the braze material was determined for each set of braze parameters (ASTM D3528). In addition, tension tests of the base material were performed before and after the thermal treatment of the sandwich specimens, in order to characterize any change in base material properties due to the optimal braze thermal cycle (ASTM E8).

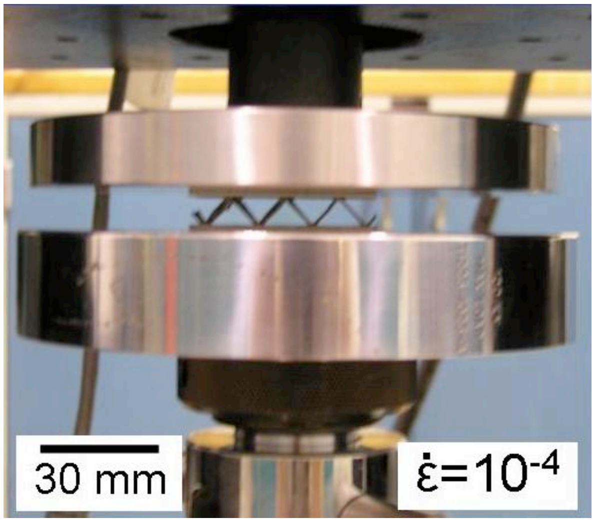

Figure 2: Set-up of flatwise compression testing.

Results

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

	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
Monolithic	870.4 (± 13.7)	913.3 (± 19.4)	16.1 (± 2.7)
Weld+HIP	830 (± 11)	906.4 (± 15.8)	9.1 (± 2.8)
DB+HIP	754.1 (± 12.9)	848.5 (± 13.7)	13.8 (± 2.4)
Braze+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)

Table II: Strength-Ductility measurements of monolithic and joined Ti-6Al-4V. The values in parenthesis are 2 standard deviations from the mean.

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 does 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 m) covering the entire interface. In all cases (except the Braze only), the microstructures were homogeneous throughout the titanium bulk and along the joining interface.

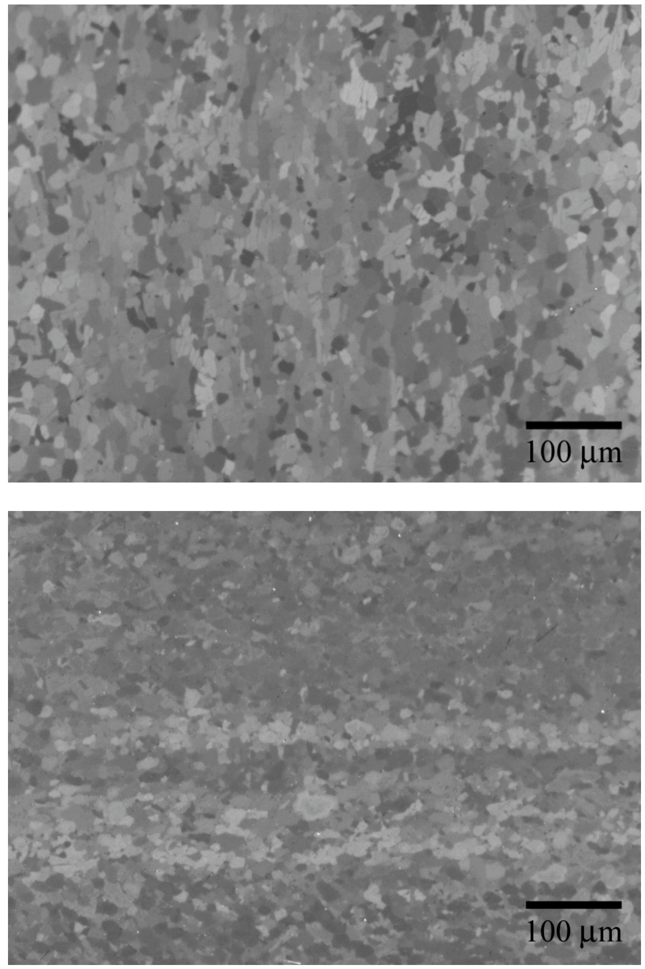

Figure 3: (Top) Monolithic Ti-6Al-4V microstructure, (Bottom) Weld + HIP Ti-6Al-4V microstructure.

The resulting compressive stress-strain plots for the sandwich panel specimens can be viewed in Fig. 5-6. Peak compressive strength ranged from 5.4 MPa to 7.8 MPa with an average 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.[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 and resulting facesheet perforation.

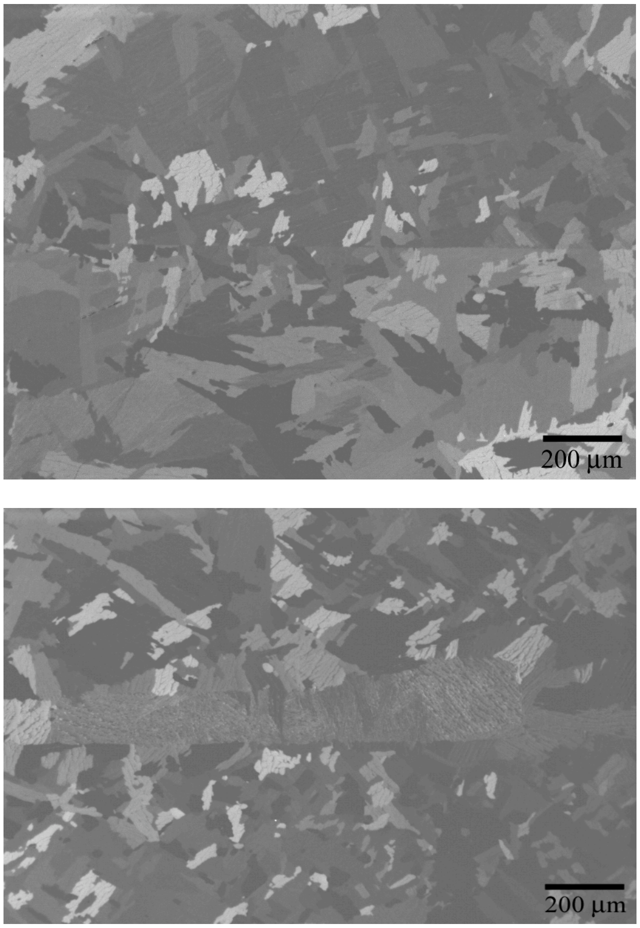

Figure 4: (Top) DB + HIP Ti-6Al-4V higher magnification image, (Bottom) Braze + HIP Ti-6Al-4V higher magnification image.

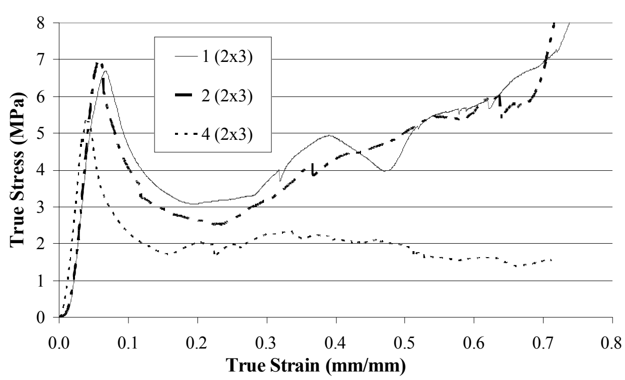

Figure 5: True stress-strain results for core compression tests (Joint Failure)

The average strength of the BRAZ1954 alloy can be viewed in Fig. 7 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.

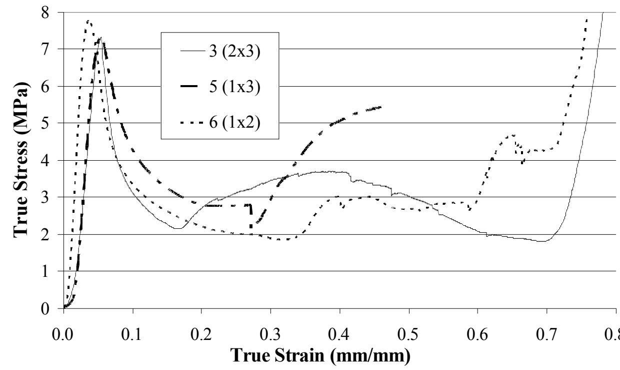

Figure 6: True stress-strain results for core compression tests (Strut Failure)

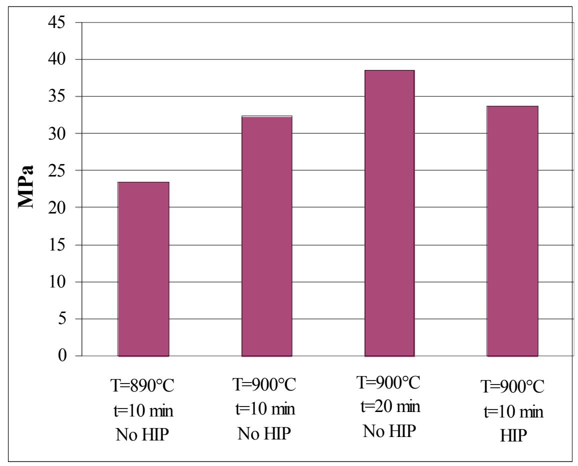

Figure 7: Double-lap shear strength results for CP titanium brazed with BRAZ1954 for described thermal cycles.

The subsequent tensile true stress-strain plots for the base material, CP titanium, can be viewed in Fig. 8. Prior to thermal treatment, yield strength and percent elongation were measured to be 627 MPa and 30.4%, respectively. After the base material underwent the corresponding braze cycle, yield strength and percent elongation were measured to be 600 MPa and 9.8%, respectively. Thus some degradation in base material properties occurred during joining of the structure.

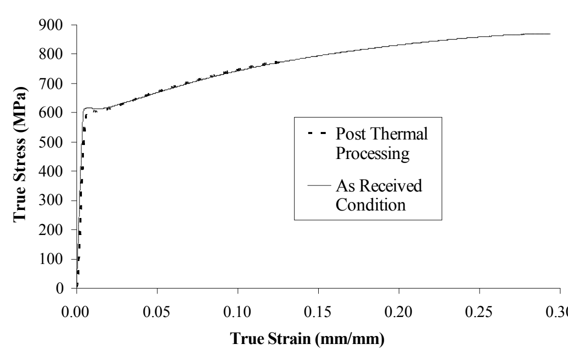

Figure 8: True stress-strain results for as-received and post thermally processed CP titanium (0.024 mm thick sheet perpendicular to the rolling direction)

Discussion

The joining of monolithic titanium section of this study was successful in determining the validity of replacing an E-beam welding plus hot isostatic pressing (E-beam+HIP) process in the encapsulation of a ceramic within a titanium structure. The testing of the different joining methods highlighted some definite candidates for the replacement of the E-beam+HIP process, such as the Weld+HIP, and demonstrated the need for optimization in certain processes (DB+HIP and Braze+HIP) to get viable replacements. The Braze only method was the least successful joining option which would require the most development before a possible solution may be achieved. The HIP procedure was verified as a current necessary step to get adequate joint properties. The HIP procedure (900ºC, 2 hours) did not diminish the base Ti-6Al-4V properties (the strength/ductility properties are still within the specification), and did not measurably alter the 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 (over 40%). However, a ductility of 9% 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 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 good 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 saw the same thermal treatment. The high temperature braze or diffusion bond cycle (1000ºC for 10 minutes) 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 performance is not ideal for titanium joining to be used in ceramic encapsulation or structural applications. However, the DB+HIP or the Braze+HIP process should be workable 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 (960ºC). A transition to an alternative, lower temperature braze material (such as BRAZ1954) is a more reasonable option which should allow a Braze+HIP type procedure to successfully be used for titanium joining for ceramic encapsulation.

The Braze only treatment was the least successful in creating a good 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 bond line. A significant increase in bonding pressure during brazing should improve braze flow and enhance wetting 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.

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.[2] Therefore, an adequate bond at each joint interface must be achieved such that micro-stretching of the facesheets is initiated, and failure occurs due to buckling of the struts.

For the samples tested in this study, peak strength and panel failure mechanism could be directly correlated through post-test inspection of the test samples. For specimens 1, 2, and 4, (Fig. 5) joint failure led to reduced peak strength, whereas for specimens 3, 5, and 6, (Fig. 6) joint strength was adequate, such that subsequent buckling of the struts initiated failure. 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 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.[2]

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.[5] Since similar thermal cycles were used in both studies, the only parameter which 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 primary 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 minutes to 20 minutes (at 900ºC) 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 parent material. Finally, adding a post-brazing HIP cycle did not result in any significant increase in braze strength, 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 parent 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 the braze cycle, 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 would occur entirely due to elastic buckling of the struts.[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 important factor. 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.

Summary

- Braze+HIP and Diffusion+HIP are both functional options for encapsulating a ceramic within titanium structures. 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 the 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 bonding can be directly related to the low pressure applied during the brazing cycle. Further work could determine whether an increased axial load during the brazing cycle could improve the bonding 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, however the elevated processing temperature minimizes the allowable pressure on the structure during brazing (to avoid creep deformation) and enables adverse changes to the 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 and degradation of parent material properties. A lower temperature brazing alloy with more pressure applied during brazing may provide a stronger bond.

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3	GDLS G TEAL C O'ROURKE C NIESE 38500 MOUND RD STERLING HTS MI 48310-3200
5	BAE SYSTEMS J DORSCH B CROOM E SAVAGE J TURN D SCHADE PO BOX 359 SANTA CLARA CA 95050
1	OSD OUSD(A&T)/ODDR&E (W) L SLOTER 1777 N KENT ST STE 9030 ARLINGTON VA 22209
4	DIR DARPA S WAX A ALVING L CHRISTODOULOU D HONEY 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	UNIV OF DELAWARE DEPT OF MECH ENGRG J GILLESPIE 201 SPENCER LAB NEWARK DE 19716

ABERDEEN PROVING GROUND

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18	DIR USARL AMSRD ARL WM MB T BOGETTI A YIOURNAS AMSRD ARL WM MC T JESSEN M MAHER AMSRD ARL WM MD B CHEESEMAN E CHIN J CHINELLA G GILDE K DOHERTY (3 CPS) J MONTGOMERY J TICE (3 CPS) AMSRD ARL WM TA C HOPPEL E HORWATH C KRAUTHAUSER