Comparison of Braze and Solder Materials for Joining Titanium to Composites

Studies were conducted to determine the tensile load-carrying ability of joints for a curved surface and the shear strength of joints in a butt-strap lap test

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There is considerable interest in joining dissimilar materials such as metals to carbon-carbon (C/C) composites for a variety of aerospace and land-based applications (Refs. 1–3). In particular, thermal management systems are being developed for various space exploration applications that require the joining of metal tubes to C/C composite face sheets (Ref. 4). For this reason, studies are underway to determine the effectiveness of various braze and solder approaches toward joining Ti tubes to different C/C face-sheet materials.

In an earlier study (Ref. 5), a tube-plate tensile test was developed to determine the tensile load-carrying ability of Ti tubes brazed to C/C plates. The three different braze materials used in that study all wet the Ti and the C/C composite and appeared to strongly bond to the Ti and the C/C substrates for simple flat-on-flat joints (Ref. 6). The simple tube-plate technique was very good at illuminating such issues as how well the braze spreads to fill in the region between the tube and the plate, which dictates the bonded area and ultimately the load carrying ability of the joint. In an earlier study, higher temperature brazes were used on a lower conductivity C/C composite (woven T300 fibers; resin-derived carbon matrix). In this study, lower temperature braze materials and one solder were used to braze similar tube-plate structures as well as more conventional butt-strap lap shear specimens for Ti and a higher stiffness (woven P120 fibers), higher conductivity CVI carbon matrix composite.

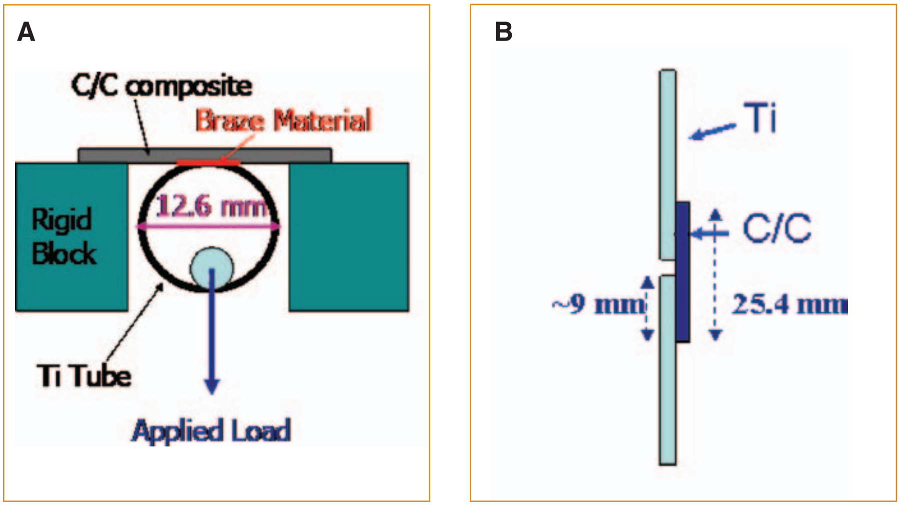

Fig. 1 — Schematic representations of joint tests. A — Tube-plate tensile; B — butt-strap tensile.

Experiment Details

Two types of joint structures were used in this study. For all the structures, commercially pure Ti (Grade 2, TIMET Inc., Mo.) was joined to a C/C composite consisting of stacked three-harness satin 2D woven carbon fabric (P120) and chemically vapor infiltrated (CVI) carbon matrix composite (Goodrich Corp., Santa Fe Springs, Calif.). The C/C thickness was approximately 1.2 mm.

The composition and liquidus temperatures of braze and solder materials used in this study are listed in Table 1. The braze alloys were obtained from Morgan Ad-

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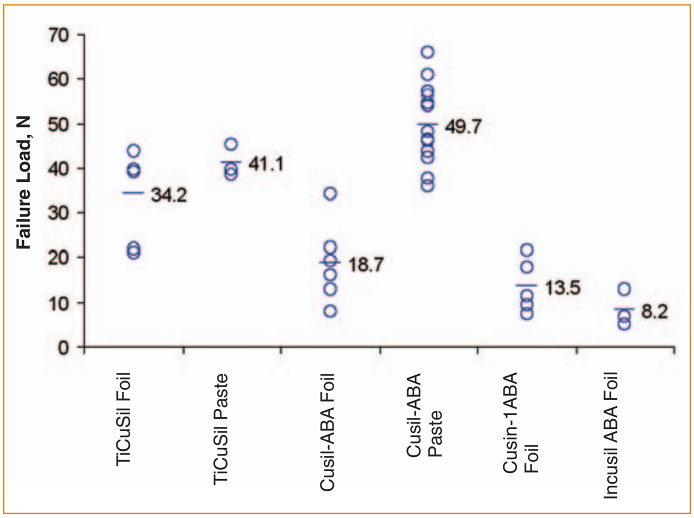

Fig. 2 — Tube tensile failure loads for different braze approaches.

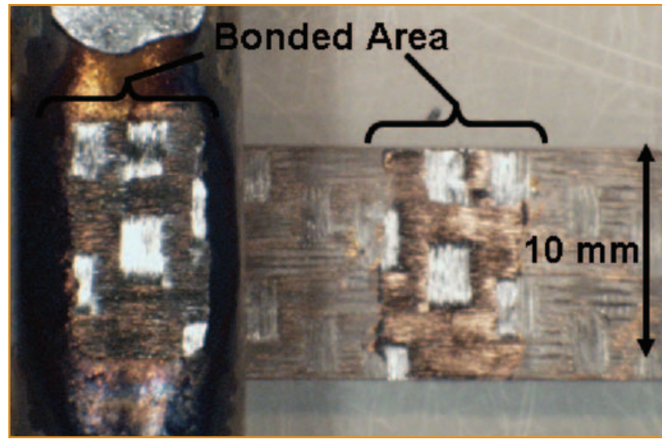

Fig. 3 — Tube and C/C plate fracture surfaces for CuSil-ABA paste braze material showing the bonded area of the outer ply of C/C brazed to the Ti tube (left) and C/C plate (right).

Table 1 — Braze and Solder Properties

Braze/Solder	Composition	Liquidus Temp., °C
TiCuSil Braze	68.8 Ag, 26.7 Cu, 4.5 Ti	900
CuSil ABA Braze	63.0 Ag, 35.3 Cu, 1.8 Ti	815
CuSin-1 ABA Braze	63.0 Ag, 34.3 Cu, 1.8 Ti, 1.0 Sn	806
InCuSil ABA Braze	59.0 Ag, 27.3 Cu, 1.3 Ti, 12.5 In	715
S-Bond 400 Alloy Solder	Zn, Ag, Al, with trace amounts of Ga and Ce (Ref. 7)	410–430 (Ref. 7)

Table 2 — Tube-Plate Tensile Results

Braze	#Tested ⊥;//	Failure Load, N ⊥; //	Stress, MPa ⊥;//
TiCuSil Paste	3;0	41.1 ± 3.0[(a)]	0.45 ± 0.02
TiCuSil Foil	6;6	34.2 ± 10.0; 34.3 ± 12.8	0.86 ± 0.44; 0.39 ± 0.14
CuSil ABA Paste	11;6	48.7 ± 9.3; 47.8 ± 13.0	0.47 ± 0.09; 0.32 ± 0.18
CuSil ABA Foil	6;0	18.0 ± 9.9	0.55 ± 0.19
CuSin-1 ABA Foil	3;3	15.1 ± 5.7; 5.8 ± 2.2	0.68 ± 0.44; 0.56 ± 0.06
InCuSil ABA Foil	5[(b)]; 0	8.2 ± 4.1	NA

(a) Standard deviation.
(b) Two specimens failed in handling for InCuSil foil. It was apparent that this was a poor braze for joining Ti to this C/C composite. The bonded area was not continuous, so the determination of stress was not performed.

vanced Ceramics. Braze foils, ~ 50 μm thick, were used in all cases. For CuSil ABA and TiCuSil, joints were fabricated using a paste form of the braze as well. The braze and solder materials' processing temperatures were always performed a few degrees higher than the liquidus temperature for each braze. Soldering was performed by S-Bond Technologies, LLC, Landsdale, Pa. The soldering temperature was approximately 420°C (Ref. 7), significantly lower than the braze materials' processing temperatures. Soldering also involved a proprietary metallization treatment to the C-C surfaces.

Two types of joint specimens were fabricated: tube-plate tensile specimens and butt-strap-tensile (BST) shear specimens — Fig. 1. Tube-plate tensile tests were performed on all the braze systems but not on the solder system. Butt-strap-tensile tests were performed on most of the braze systems and on the solder system. The C/C panels were machined into 2.54 × 1.26-cm plates that were joined to 1.26-cm-diameter × 2.54-cm-long tubes for the former and 1.26 × 75-mm lengths of a Ti flat plate for the latter test configuration, respectively.

Investigation Results

Tube-Plate Tensile Tests

The tube-plate tensile data are shown in Fig. 2 for four different braze systems. At least three specimens were tested for each condition. The TiCuSil and CuSil-ABA braze compositions were tested in paste as well as foil form. The CuSil-ABA paste system had the best load-carrying ability of all the braze systems followed by the TiCuSil paste and TiCuSil foil systems. All three systems showed excellent braze spreading and large metallic bonded areas. Figure 3 shows a typical fracture surface of a tube-plate specimen where the braze spread and strongly bonded to the outer C/C ply over a significant distance of the plate. The CuSil-ABA foil system as well as the CuSin-1 ABA and InCuSil ABA braze systems, which were the two lower-temperature systems, all showed poorer load-carrying ability. For these systems, considerably poorer braze

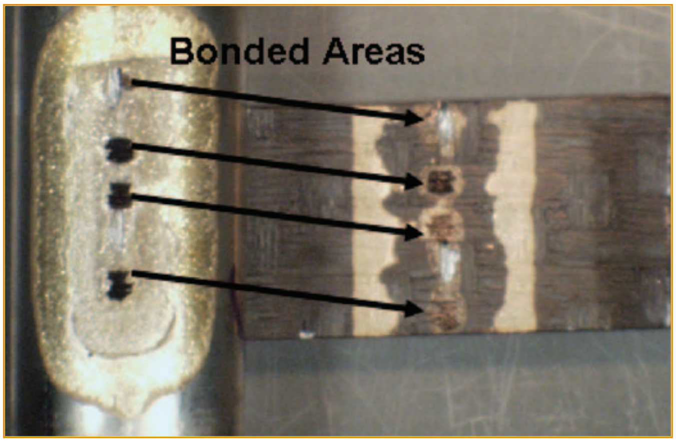

Fig. 4 — Tube and C/C plate fracture surfaces for InCuSil ABA foil braze material showing the distinct bonded areas of the outer ply of C/C brazed to the Ti tube (left) and C/C plate (right).

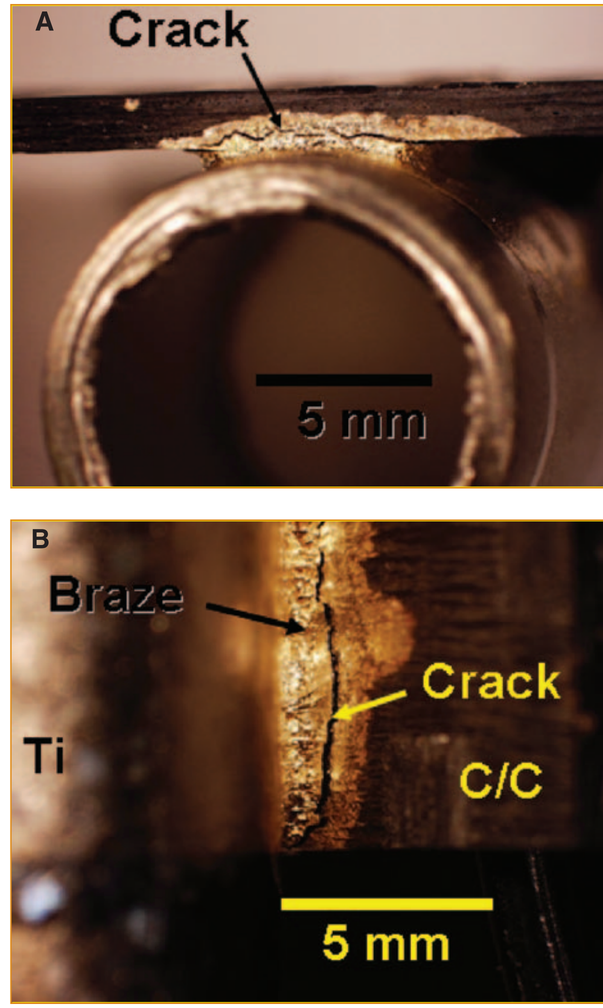

Fig. 5 — TiCuSil paste brazed tube-plate specimen showing a crack after processing. A — Edge-on perpendicular to the tube axis; B — at an angle parallel to the tube axis.

spreading and smaller bonded areas were observed — Fig. 4. Note that in Fig. 4 (InCuSil ABA foil), metallic bonding of the braze material to the C/C composite was patchy, predominantly only the outer tows of the C/C surface ply were bonded. This was one of the poorest braze spreading examples. For the CuSil-ABA foil and CuSin-1ABA foil, the bonded area usually extended over the width of the C/C plate, but the distance the braze spread along the length of the plate was significantly less compared to Fig. 3.

Using the size of the bonded areas, the apparent failure stress of the joints can be determined. Table 2 lists the average failure load and failure stress for the different braze combinations. The data were separated for each braze system based on the orientation of the outer fibers on the surface of the C/C composite. The C/C composite is made up of stacked 2D harness satin woven cloth where the exposed side of the composite is dominated by the fiber tows either oriented perpendicular or parallel to the axis of the tube (for example, most of the surface fiber tows in the harness satin weave are oriented perpendicular to the tube axis in Figs. 3, 4). In the earlier study (Ref. 5), it was observed that fiber tows orientated perpendicular to the tube axis had higher load-carrying ability compared to the case where the fiber tows were predominantly oriented parallel to the tube axis. This effect was not as noticeable for the composite system tested in this study. The composites used in this study have a 3 harness satin weave (i.e., each fiber tow crosses over two perpendicular tows and then under one perpendicular fiber tow) and a larger number (2000) of fibers per tow compared to the composites used in Ref. 5 (5 harness satin, 1000 fibers per tow). For the composites of this study, the net effect is a lower aspect ratio of surface tow orientation since the tow widths are wider and the outer tows only cross over two perpendicular tows compared to four perpendicular tows in the 5 harness satin weave. Therefore, it is not surprising that the failure loads for perpendicular and parallel oriented composites were not significant in this study (Fig. 2 combines all the data of Table 2).

The TiCuSil foil was also used in Ref. 5 with the T300 resin-derived carbon matrix composites. For that system, the failure loads were less than 10 N compared to 34 N for the P120 CVI carbon matrix plates used in this study and the failure stress was on the order of ~ 0.2 MPa compared to ~ 0.6 MPa for the P120 CVI carbon matrix plates used in this study (Table 2). This is commensurate with the difference in interlaminar tensile (ILT) strengths between the two systems. For the T300 resin-derived carbon matrix composites, the ILT strength (ASTM C1468) was found to be 2 MPa, whereas the ILT strength of the P120 CVI carbon matrix composites of this study were 6.5 MPa (Ref. 8).

One issue of concern with the braze systems was the presence of cracks after processing within the braze reaction layer — outer-ply of the C/C. Figure 5 shows a crack for a TiCuSil paste specimen. This was most apparent for the TiCuSil specimen, which would be expected due to the higher processing temperature of the TiCuSil (see discussion below). Even though these cracks were more apparent and larger for the TiCuSil specimens, tensile load-carrying ability of the tube-plate configuration was primarily dependent on the spreading of the braze, i.e., bonded area of the C/C.

Butt-Strap Lap Tensile Shear Tests

Butt-strap lap tensile (BST) tests were performed as shown in Fig. 1B for the

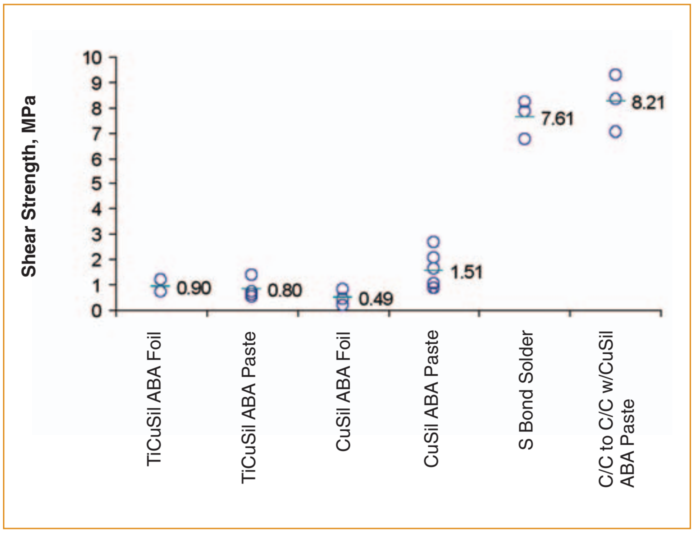

Fig. 6 — Shear strength of different braze and solder joints.

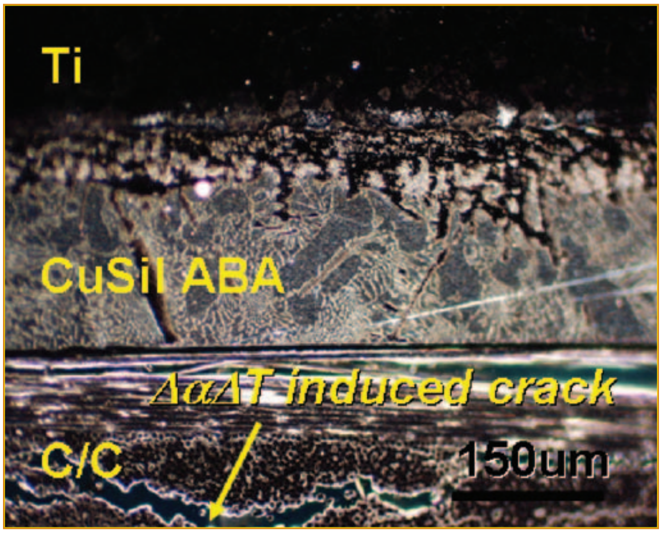

Fig. 7 — Optical micrograph of a typical crack within the outer ply of the C/C for a joint region of a Ti plate joined to C/C composite with CuSil ABA paste.

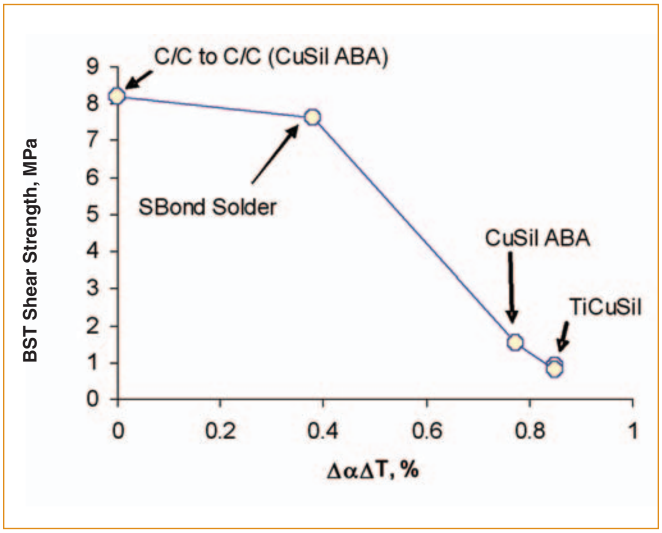

Fig. 8 — Effect of the estimated thermal-induced residual elastic strain in the joint on shear strength. The CuSil ABA foil joint data were not used because this braze material did not spread and bond the lap section effectively.

TiCuSil and CuSil ABA braze compositions and one solder material (S-Bond). In addition, a BST test was performed for the C/C composite brazed to the C/C composite using the CuSil ABA paste. The S-Bond is processed at a significantly lower temperature (Table 1), which should minimize the buildup of thermal stresses between the Ti and the C/C. For the case of C/C brazed to C/C, no thermal stresses would be expected between the joined plates since they are the same material. Only thermal stresses that would occur between the braze and the C/C would develop, which are expected to be minor due to the ductility of the braze.

Figure 6 shows the shear strength results for the different braze and solder combinations. At least three specimens were tested for each combination. A significant increase in shear strength was observed for the S-Bond solder and C/C brazed to C/C. It should be noted that all of the brazes spread and bonded the entire area where the Ti and C/C plates overlapped except for the CuSil ABA foil specimens, which accounted for the poor shear strengths for that system.

Formation of Cracks

Cracks were observed within the outer ply of the C/C composite-braze reaction layer (Fig. 7), which were due to the thermal stresses caused on cool down due to the difference in thermal expansion coefficients between the Ti (8.6×10^{-6}/°C) and the C/C (-1×10^{-6}/°C). The crack in Fig. 7 extended several millimeters along the length of the specimen. These preexisting cracks were the initial flaw sources for joint failure of the Ti to C/C brazed joints. No cracks were observed in the S-Bond solder joints or the C/C to C/C brazed joints.

Since thermal-induced residual stresses appear to control joint performance for these systems, a first-order approximation of the thermal strains within the joint was estimated using the simple relationship (assuming elastic behavior) $\Delta\alpha\Delta T$, where $\Delta\alpha$ is the difference in the thermal expansion coefficients between the two plates of the joint and ΔT is the processing temperature of the braze or solder (Table 1) subtracted by the test temperature (25°C). The estimated thermal-induced residual strain on shear strength is plotted in Fig. 8. For the braze joints, the thermal-induced strains would be very high and it is not surprising that they are accommodated by cracking within the outer ply of the C/C. However, the formation of the cracks significantly reduces the shear strengths of those joints. Apparently the buildup of strains on the order of 0.4% could be accommodated elastically or more likely via plastic deformation within the S-Bond solder itself since cracking in the C/C was not observed. Not enough tests were performed to determine if the difference between the S-Bond solder joint of Ti to C/C was statistically significantly lower than the CuSil ABA paste joint of C/C to C/C. However, it is evident that the CuSil ABA paste provides a reasonable joint strength for C/C to C/C.

Conclusions

Two-dimensional woven C/C composites with high-conductivity carbon fibers were joined to Ti tubes and plates with both braze and solder approaches. CuSil ABA paste and TiCuSil braze materials performed the best of the braze concepts evaluated due to their superior spreading and resulting bonded joint area. However, due to the buildup of thermal stresses during cooling of the joined structure from the braze processing temperature, cracks within the outer layer of the C/C composites formed limiting the joint strength. The lower-processing temperature solder proved to be a much stronger joint when tested in shear since the residual stresses were sufficiently low to prohibit processing-induced cracks in the C/C composite. Relatively high joint shear strengths were also measured for C/C plates joined to C/C plates with a CuSil ABA braze.♦

Acknowledgments

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