A Simple Test to Determine the Effectiveness of Different Braze Compositions for Joining Ti-Tubes to C/C Composite Plates

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ABSTRACT

A simple tube-plate joint tensile test was implemented to compare the effectiveness of commercial brazes, namely, TiCuNi, TiCuSil, and Cu-ABA, used for bonding Ti-tubes joined to C-C composite plates. The different braze systems yielded different; yet, repeatable results. The Cu-ABA system proved to have about twice the load-carrying ability of the other two systems due to the fact that the bonded area between the braze material and the C-C plate was largest for this system. The orientation of the surface fiber tows also had a significant effect on load-carrying ability with tows oriented perpendicular to the tube axis displaying the highest failure loads. Increasing the process load and modifying the surface of the C-C plate by grooving out channels for the Ti-Tube to nest in resulted in increased load-carrying ability for the TiCuSil and Cu-ABA systems due to increased bonded area and better penetration of the braze material into the C-C composite.

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INTRODUCTION

There has been a great deal of interest in developing composite-metal joining technologies for a wide variety of aerospace and ground based applications [1-3]. High conductivity carbon fiber reinforced carbon matrix (C/C) composites based thermal management components are being developed for various space exploration systems.

However, these applications require that metal tubes be joined to C/C composite plates. There are a number of joining approaches being investigated [4-5]; however, a critical need exists for simple tests that yield meaningful analysis of joint strength or load-carrying ability for these structures. Typical joint tests such as lap-type tests where two or more flat surfaces are joined together are not representative of curved tubes joined to flat plates. Therefore, a simple tube/plate “tensile” test was developed to at least address one area of concern, the strength of the joined structure when tested in tension. This test was applied to Ti-tube - C/C composite plate structures with three different braze compositions. Careful attention was paid to the effect of processing conditions and woven architecture of the surface plies on the load-carrying ability and the fracture surface. Factors that were observed to enhance joint mechanical properties led to alterations in the processing conditions and/or surface condition of the C/C which enabled higher load-carrying ability in some cases.

EXPERIMENTAL PROCEDURES

The carbon-carbon composites used in this study were obtained from Carbon-Carbon Advanced Technologies (CCAT), Inc., Fort Worth, TX. These composites were made from T-300 C fibers and resin-derived carbon matrix. The composite panels were sliced into approximately 2.54 cm x 1.25 cm x 0.25 cm pieces. Commercially pure Ti (Grade 2) tubes from Titanium Industries, Inc., (Cleveland, OH) were cut into 2.54 cm lengths, and joined to C/C using intervening braze foils. The commercial brazes were obtained from Morgan Advanced Ceramics, Inc., and included Cu-ABA, TiCuNi, and TiCuSil. The composition, physical and mechanical characteristics of these brazes are summarized in Table 1. The braze foil thickness was ~50 m. All the materials were ultrasonically cleaned in acetone for 10 min. prior to their use. The braze foil, cut to the size of Ti and C-C plates, was sandwiched between them, and a normal load was applied to the assembly to hold them together. The baseline process load was 30 g per specimen. Process modifications were made as will be described below to enhance load-carrying ability. The assembly was heated to the brazing temperature under vacuum, isothermally held for 5 min., and then cooled to room temperature.

A typical "tube tensile test" specimen and a schematic of the test setup are shown in Figure 1. The test consisted of mounting the flat C-C plate on a rigid block with a 19 mm opening and pulling the tube in tension with a universal testing machine (Instron 4502, Canton, MA). A steel rod was inserted through the tube and steel leaders (45 lb test, Eagle Claw, Denver CO) were attached to the rod and to a swivel mechanism on the load cell. The joint structure was loaded at a cross-head speed of 1mm/min. At least five to nine specimens were tested for each condition. The peak load was recorded to measure the load-carrying ability of the joint. The fracture surface was examined to determine the fracture location and nature and extent of bonding.

RESULTS AND DISCUSSION

The load-carrying ability of the joints fabricated under standard and modified process conditions are described below.

Joined Structures: Standard Process Conditions

The failure loads of the tube/plate tensile tests for the three different braze compositions are shown in Figure 2a. The C/C plate widths varied from 11 mm to 14 mm so the data is also plotted as load divided by the plate width in Figure 2b. Two important observations are of note. First, the Cu-ABA braze composition had the highest load-carrying ability of the three braze materials for a given C/C orientation. Second, joint structures with the outer ply woven fibers of the C/C composites oriented perpendicular (Figure 3) to the tube axis had a higher load-carrying ability than when oriented parallel (Figure 4) to the tube axis.

Fracture always occurred within the surface ply of the C/C composite (Figures 3 and 4) which indicates a stronger bond between the braze material and the Ti-tube or C/C composite than the strength within the outer ply itself. Joint structures with higher load-carrying ability typically had a larger "bonded area" between the braze material and the

C/C composite. Figure 5 shows typical fracture surfaces for a joint structure using TiCuNi and Cu-ABA as the braze material. The Cu-ABA bonded area (Figure 5b) is significantly greater than the TiCuNi (Figure 5a) or the TiCuSil (Figure 3b) which corresponds to significantly greater load-carrying ability for the Cu-ABA. Evidently, the Cu-ABA better wets and spreads the C-C plate during the brazing process than the other two braze compositions [5].

From the bonded area, an average "strength" of the C/C-braze joined region can be determined and is plotted in Figure 6 for the different braze compositions and C/C composite orientations. For a given C/C orientation, the strengths are about the same for the joint structures with the three different braze materials. This indicates that the primary controlling factor for fracture is the strength of the outer ply of the composite and load-carrying ability is dictated by the bonded area of the braze and composite. It is interesting to note that the TiCuNi braze had slightly higher strengths (Figure 6) but had relatively low load-carrying ability (Figure 2) for a given orientation.

Joint structures with fibers oriented perpendicular to the tube axis are stronger than those with fibers oriented parallel to the tube axis for each braze material. Therefore, fiber orientation is also a factor that dictates the load-bearing capability of the joint, i.e., for the same bonded area, joined structures with fibers oriented perpendicular to the tube axis will carry greater loads.

The reason for the increased load-carrying ability of perpendicular oriented joint structures appears to be the fact that there are a greater number of tows bonded to the brazed tube in this orientation compared to the parallel orientation (compare Figures 3 and 4). In addition, the lengths of the tows brazed to the tube are shorter when oriented perpendicular to the tube axis, at least for bonded areas where the height of the bonded area is smaller than the length for a tow to crossover four tows in the five-harness satin woven architecture. The process of joint failure involves fracturing the outer ply of the composite. There is a reaction zone near the surface of the composite [5] and also the existence of some microcracks due to the difference in thermal expansion between Ti and the C/C composite. As a result, higher loads are required for a greater number of shorter length tows reinforcing microcracked surface plies than a fewer number of longer length tows.

Since failure occurs within the outer ply of the composite, the strength of these joint structures is expected to be related to the ply strength of the woven C-C composite. The interlaminar tensile strength of these C/C composites was reported to be 4.1 MPa [6], an order of magnitude higher than the bond strength measured based on the failure load and bonded area of the surface ply. Obviously the loading condition on the surface ply of a joint structure induces stress-concentrations and other fracture modes on fiber tows leading to joint failure at stresses lower than the composite interlaminar strength. However, it stands to reason that a higher interlaminar strength composite, such as some 3D woven-architectures, would have improved load-carrying ability.

Joint Structures: Modified Process Conditions

Based on the findings above, two simple alterations to joint processing were performed in order to try and maximize the load carrying ability of joined structures. First, it was decided to "groove" C-C plates (Figure 7a and 7b) using a round file in order to increase the bonded area of the joint and to penetrate braze-material into the interior plies in the woven architecture. It was found that higher loads were required to effectively spread the braze material into the groove. Therefore, joint structures with standard flat surface C/C composite plates were fabricated with the same processing load that was used for the grooved specimens in order to determine the effect of process load on joint load-carrying ability.

The load and stress data are plotted for the standard 30 g process load on flat C-C composites, the increased 120 g process load on flat C-C composites, and the 120g process load for grooved C-C composites in Figures 8 and 9 for TiCuSil and Cu-ABA braze joint structures, respectively. Note that the stress is derived for the bonded portion of the C/C only, and not the entire circumferential area within the tube, i.e., the load data is more indicative of the load-carrying ability rather than stress. The TiCuNi braze system was attempted but only filled in the groove region poorly resulting in poor failure loads. The TiCuSil braze joint structures usually only partially filled in the groove region (Figure 10a) resulting in partial bonded areas and poorer overall load carrying ability compared to the nearly always complete bonding of the grooved region for the Cu-ABA braze joint structures (Figure 10b).

For the TiCuSil system, load-carrying ability increased only for the perpendicular oriented joint structures with the additional process load; however, the grooved C-C plate structures resulted in significantly higher failure loads for both orientations (Figure 8a). The stress also increased relatively the same for both orientations indicating that the bonded area did not increase as much as the increase in failure load with higher process loads and grooved C-C plates (Figure 8b). For the Cu-ABA system, both orientations showed increases in load-carrying ability with the increase in process load and then a further increase with grooved C-C plates (Figure 9a). The failure stress for both orientations also increased with process load, indicating less of an increase in bonded area (Figure 9b). However, a minimal or negligible increase in stress was observed from the flat C-C joint structures to the grooved C-C joint structures processed with the same load. Increases in failure loads without proportional increases in bonded area would be due to better penetration of the braze material; whereas, increase failure loads with proportional increases in bonded area are due to better spreading of the braze. Note that the Cu-ABA system for the same process load or C-C surface condition had about twice the load-carrying ability of the TiCuSil. Also, there was little difference in load-carrying ability for the two orientations when grooved C-C plates were brazed to Ti-tubes for both braze compositions (Figures 8a and 9a).

There was some reaction between the braze material and the Ti-tube for the 120g loaded tube structures with the Cu-ABA braze. The reaction was most severe for the grooved C-C plate specimens. In some cases the reaction resulted in depression of the tube or even a hole to be formed in the tube. Certainly this is something to be avoided for most applications and optimization of the braze conditions would need to be determined.

CONCLUSIONS

The simple tube-plate joint tensile test proved to be an effective means of evaluating the tube to plate tensile load carrying ability for joined structures with different braze materials. The three different braze systems (TiCuNi, TiCuSil, and Cu-ABA) yielded different; yet, consistent and repeatable results. The Cu-ABA had the highest load-carrying capacity. This was due to better spreading of this braze composition resulting in larger bonded areas between the braze material and the C-C composite. The orientation of the surface fiber tows also has a significant effect on load-carrying ability. Joint structures with C-C plates with exterior fiber tows oriented perpendicular to the tube axis display higher failure loads when compared to joint structures processed identical but with C-C plates with exterior fiber tows oriented parallel to the tube axis. Insights gained from the fracture surfaces of the initial joint structures led to two processing modifications: higher process loads and grooved C-C plates. Both were aimed at increasing load-carrying ability which proved successful due to increases in bonded area and braze penetration into the C-C composite. The grooved C-C plate joint structures brazed with Cu-ABA displayed the highest load carrying abilities of all the systems tested; however, instances of reaction between the Ti-tube and the braze material were observed for this system at the higher process load conditions. It is concluded that this technique offers a simple yet meaningful test for development of tube to plate joined structures.

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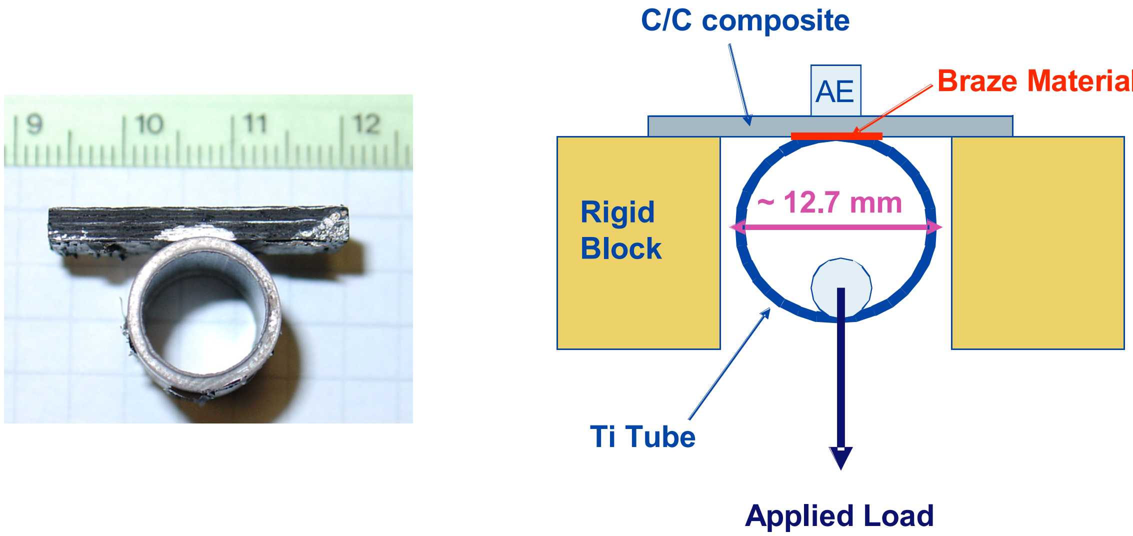
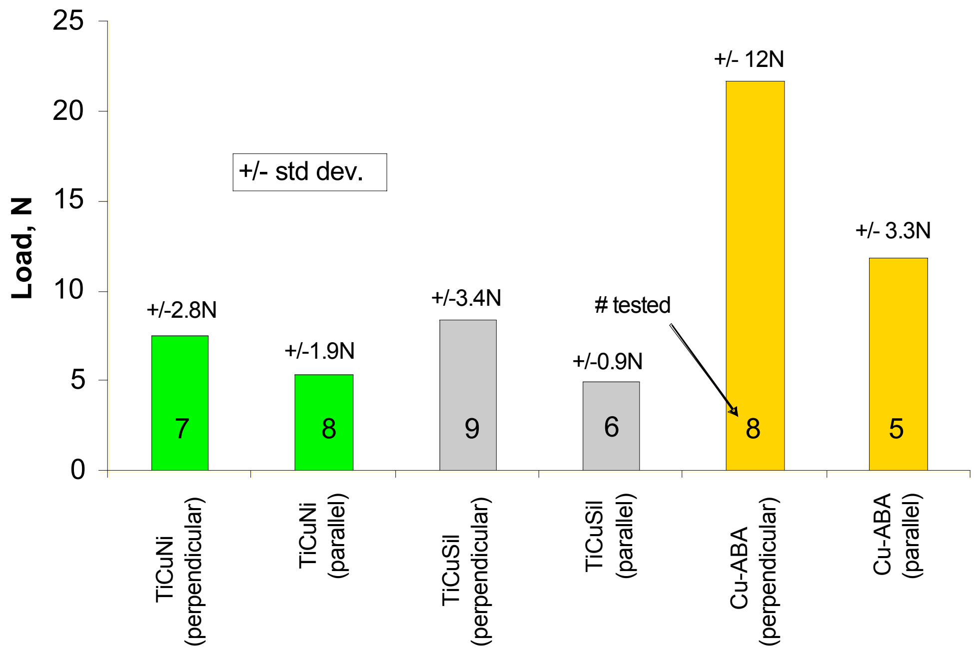
Table 1. Chemical Properties and Standard Processing Conditions of Brazes

Braze	Composition	Liquidus Temp, ^{o}C	Processing Temp, ^{o}C	CTE, 10^{-6}/K	Thermal Cond., W/m-K
TiCuSil	68.8 Ag, 26.7 Cu, 4.5 Ti	900	910	18.5	219
TiCuNi	70 Ti, 15 Cu, 15 Ni	960	975	20.3	--
Cu-ABA	92.8 Cu, 3 Si, 2 Al, 2.2 Ti	1027	1040	19.5	38

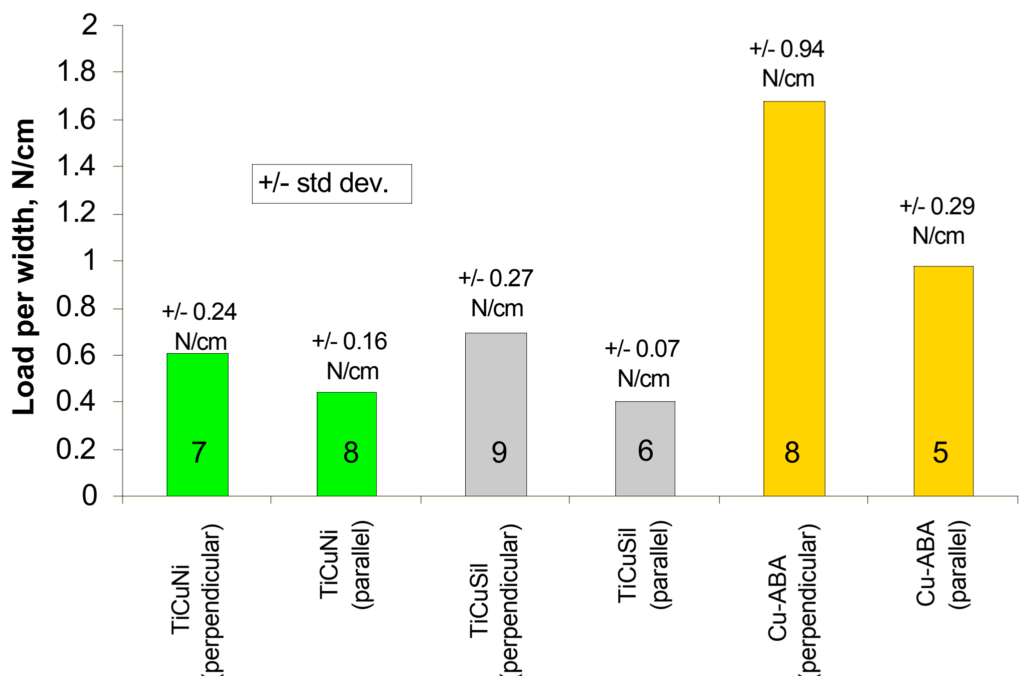


(a) (b)

Figure 1: (a) Optical photograph of specimen and (b) schematic of tube tensile test.

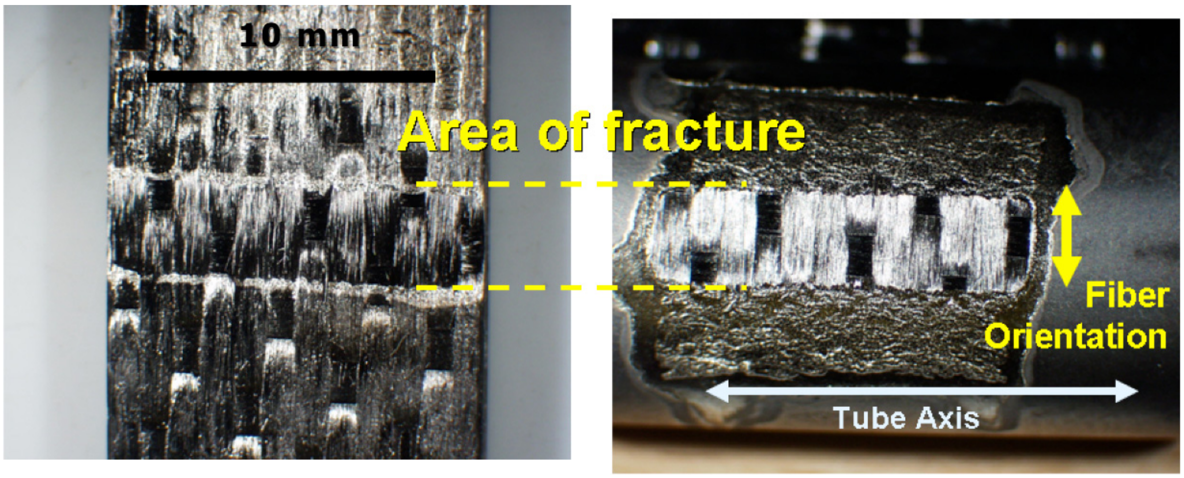


(a)



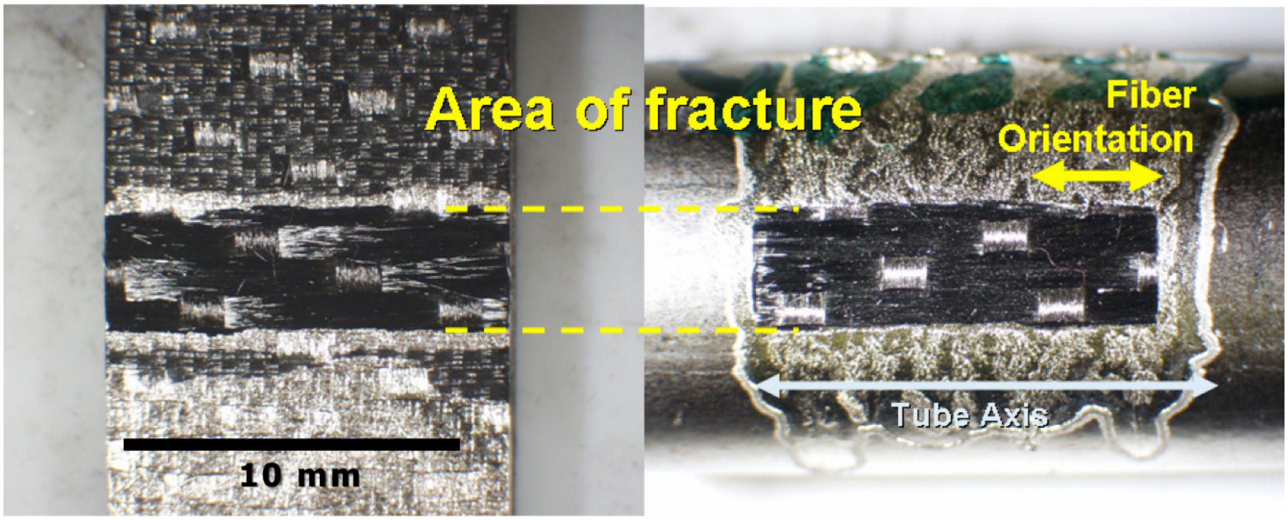
(b)

Figure 2: (a) Absolute failure load and (b) failure load divided by the width of the C/C plate for different braze and C/C orientation specimens. The numbers in the bars indicate the number of specimens tested.



(a) C/C Composite (b) Ti tube

Figure 3: Fracture surfaces of (a) C/C composite and (b) Ti tube for a TiCuSil braze specimen for fiber oriented perpendicular to the tube axis.



(a) C/C composite (b) Ti tube

Figure 4: Fracture surfaces of (a) C/C composite and (b) Ti tube for a TiCuSil braze specimen for fiber oriented parallel to the tube axis.

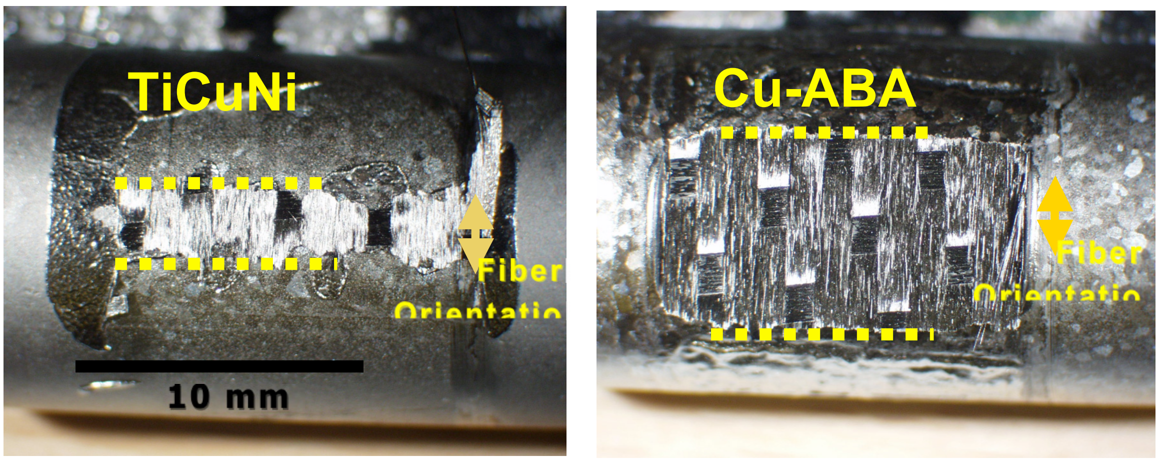


Figure 5: Typical joint structure fracture surfaces which adhered to the Ti-tube for (a) TiCuNi braze material and (b) Cu-ABA braze material.

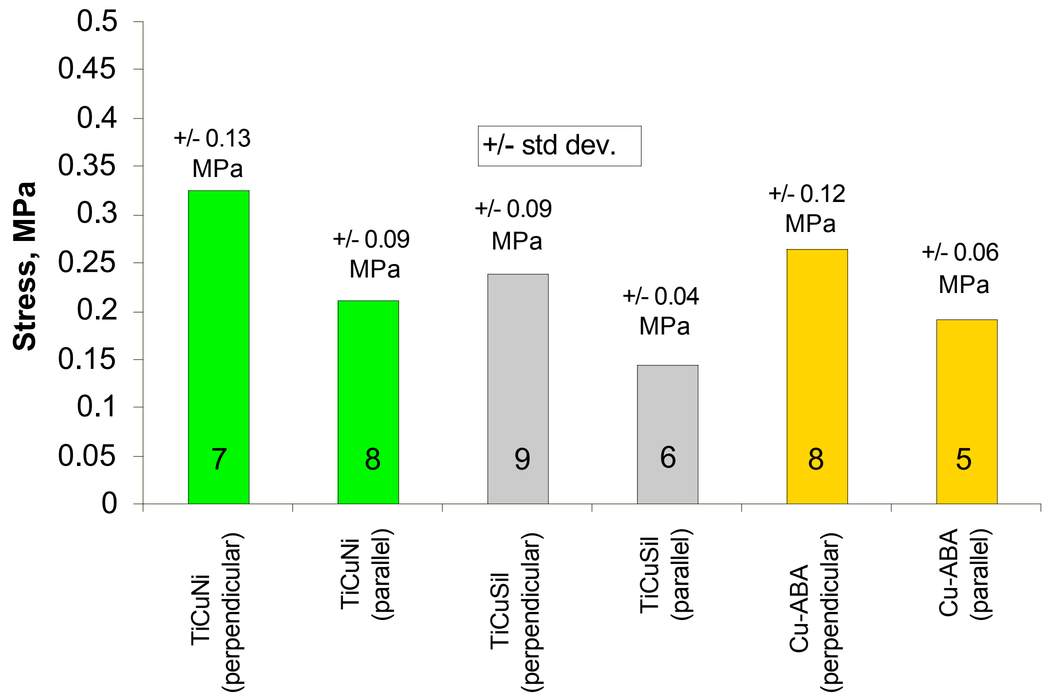
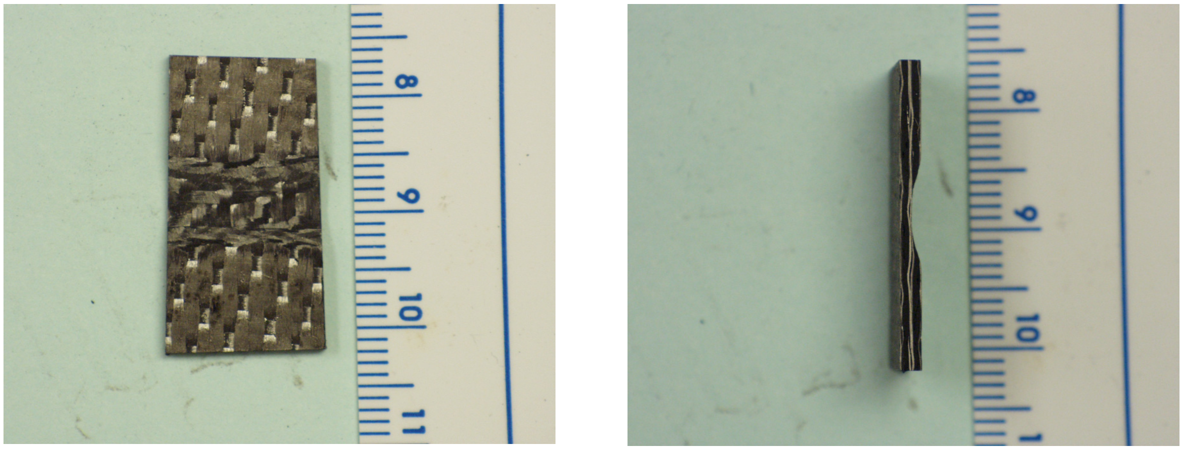


Figure 6: Average strengths of joint structures based on applied load and bonded area.



(a) (b)

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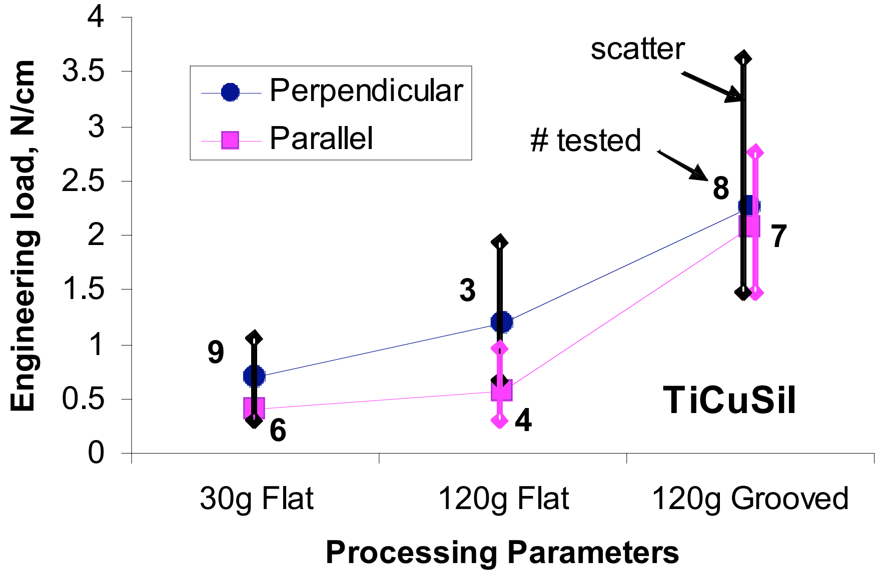
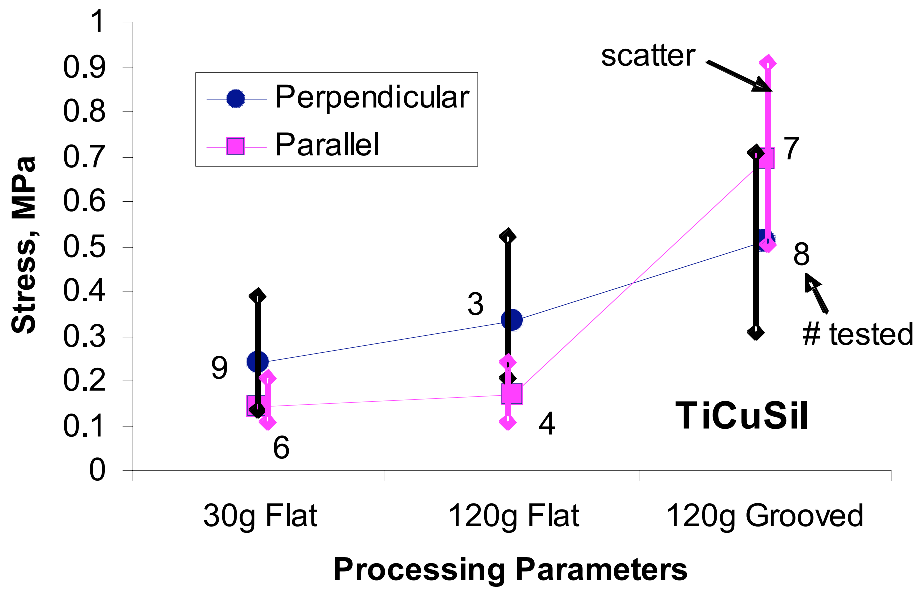
Figure 7: As-received C-C plate with groove (a and b).

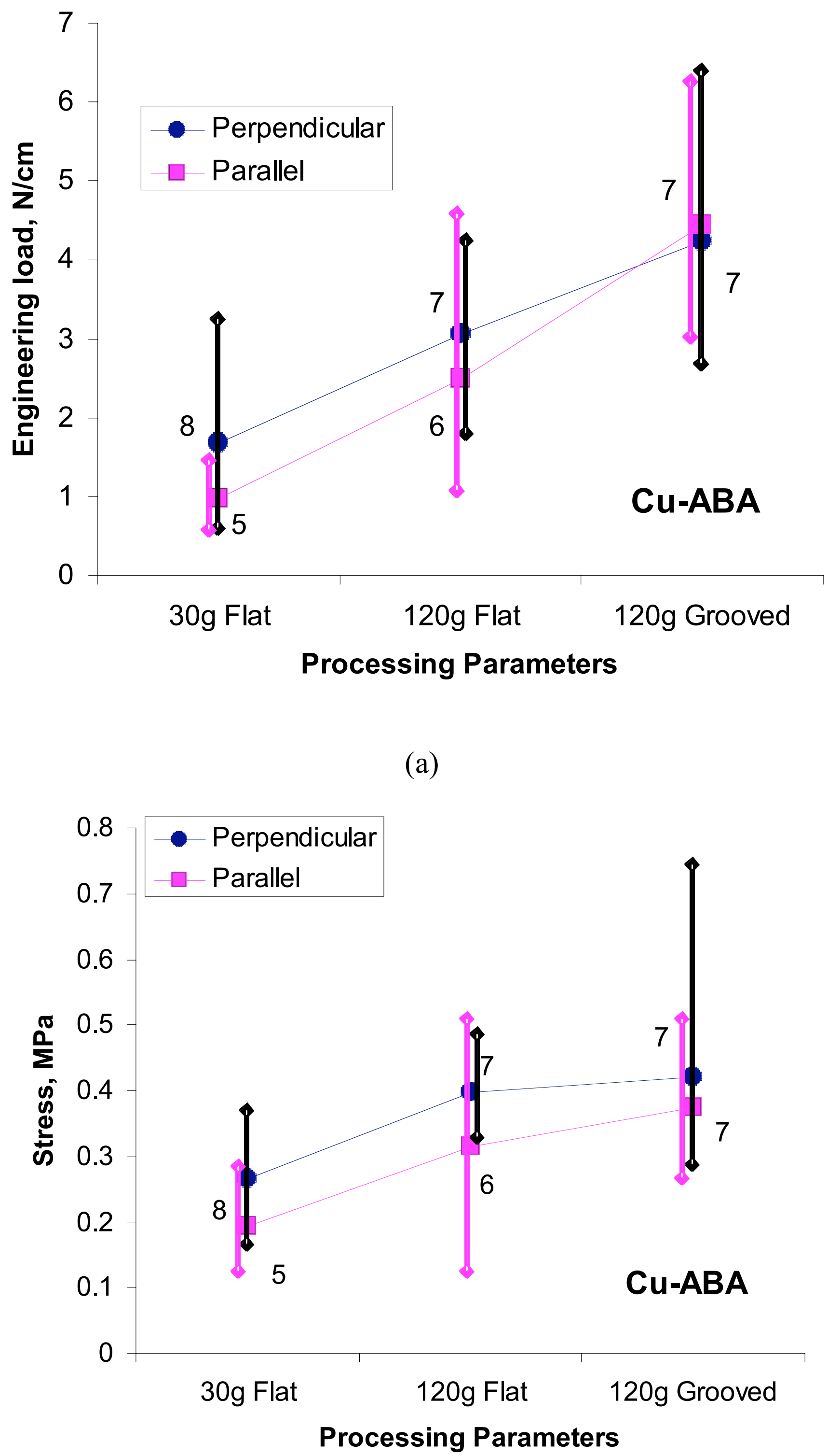


(a)



(b)

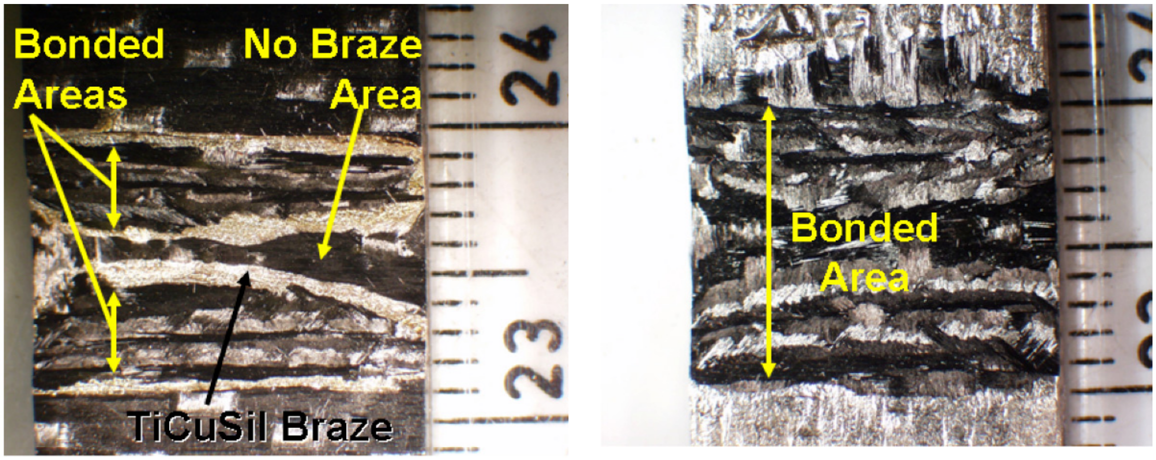
Figure 8: Effect of processing parameters for joint structures with TiCuSil braze material on (a) load-carrying ability and (b) bonded area strength.



(a)

(b)

Figure 9: Effect of processing parameters for joint structures with Cu-ABA braze material on (a) load-carrying ability and (b) bonded area strength.



(a) (b)

Figure 10: C-C plate fracture surface after tube tensile test for (a) TiCuSil braze and (b) Cu-ABA braze.