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Large Area Active Brazing of Multi-tile Ceramic-Metal Structures

by Kevin J. Doherty

ARL-RP-366 **May 2012**

A reprint from the *Proceedings From the 5th International Brazing and Soldering Conference*, Las Vegas, NV, 22–25 April 2012.

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14. ABSTRACT
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Large Area Active Brazing of Multi-tile Ceramic-Metal Structures

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Abstract

Lightweight ceramic-metal combinations are one option for advanced vehicle and other structural applications. These structures can require the fabrication of large area arrays of ceramic tiles on a metallic backing. However, the process of fabricating a combination of lightweight ceramics and metals is complicated by the need to bond these very dissimilar materials together. For severe applications, a strong bond between the ceramic and metal is required. One option for achieving this strong bonding in ceramic-metal systems is active metal brazing. The active brazing alloys wet most materials (including ceramics and corrosion-resistant metals such as titanium alloys and stainless steels) and form strong, metallurgical bonds. However, the high processing temperatures result in large strain (stress) build-up from the inherent differences in coefficient of thermal expansion (CTE) of the substrates. There are some techniques available to alleviate the strains on the ceramic, such as using an interlayer, which either has an intermediate value (between the metal and ceramic) of CTE and/or is "soft" (plastically deforms). However, it is still extremely challenging to actively braze large specimens when there is a considerable CTE gradient. This study will introduce pyramidal core structures as one of many possible interlayers between ceramic tiles and metal substrates. The processing techniques to successfully fabricate lightweight, large area ceramic-metal arrays will also be discussed.

Introduction

The desire for smaller, lightweight 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. However, to allow ceramics to achieve this promising potential, they must be incorporated into the proper armor system that prevents premature ceramic failure during bending under the ballistic load. Lightweight metals (such as titanium alloys) are armor materials and can function as structural materials with excellent strength and ductility. However, the process of fabricating a combination of lightweight metals and ceramics is complicated by the need to bond these very dissimilar materials together. A typical joining method for ceramics-metals is adhesive bonding. Joining with adhesives, such as epoxy, is convenient because it is performed near room temperature in air and is compatible with most materials. The drawbacks to adhesive bonding are the resulting low bond strengths and the low modulus. The combination of low modulus and low density creates a substantial elastic impedance mismatch with the ceramic and metal substrates. Other bonding materials such as brazes and solders typically have higher bond strengths in addition to higher moduli and higher densities than adhesives, and this lowers the elastic impedance mismatch between the ceramic and metal substrates. Zaera et al. (ref.1) explained that increasing the elastic (mechanical) impedance mismatch at the ceramic-joining media interface will decrease the amount of incident energy that is transmitted to the joining media and increase the amount of incident energy that is reflected back into the ceramic. This increased reflected energy causes an increase in the tensile stresses in the ceramic, that combined with the low bond strength of the adhesive, allows early bond rupture, radial fracture of the ceramic rear surface, and premature system failure.

The desire for stronger bonding in ceramic-metal systems has led to the examination of joining techniques that involve beneficial chemical reactions at the metal-ceramic interfaces. During the early '80s, Mizuhara and coworkers (ref. 2,3) adapted an idea from the '50s by putting an "active" component, such as titanium, directly into a brazing alloy, typically a silver-copper eutectic, to significantly improve the wetting of both metal and ceramic substrates. This initiates a one-step vacuum brazing process, known as active brazing, that wets most materials (including ceramics and corrosion-resistant metals such as titanium alloys and stainless steels) and forms strong, metallurgical bonds. The major disadvantage of using active brazing for metals and ceramics is the high processing temperature required that results in large strain (stress) build-up during cooling from the inherent differences in coefficient of thermal expansion (CTE) between metals and ceramics. There are some techniques available to alleviate the strains on the ceramic, such as using an interlayer, which either has an intermediate value (between the metal and ceramic) of CTE and/or is "soft" (plastically deforms). However, it is still extremely challenging to actively braze large specimens when there is a considerable CTE gradient.

In trying to fabricate thinner (lighter) ceramic-metal brazed combinations, it became clear that bending rigidity of the system was extremely important. Therefore, methods to introduce additional bending rigidity without adding significant weight were considered. Metallic sandwich panels consisting of solid face sheets and a low density core were focused on as possible solutions. The sandwich structures can provide both structural strength and stiffness with load-bearing potential. It is well known that sandwich plates, using strong and stiff facesheets with a low density core, possess a superior bending stiffness and strength to monolithic beams of the same mass under quasi-static loading (ref. 4).

The focus of this work is to detail the challenges associated with manufacturing lightweight multi-tile ceramic-metal active brazing samples. Specific difficulties related to reducing the metallic backing thickness will be presented. Possible interlayer schemes will be introduced with the most promising ones further explored to create larger and lighter samples. The properties and characteristics of metallic sandwich panels that are relevant to advanced structures and stress management will be discussed.

Experimental Procedures

Initially, individual ceramic-metal samples were assembled, as shown schematically in Fig. 1. The aluminum oxide used in this study was sintered AD995 from CoorsTek (Golden, CO), the metallic backing was annealed Ti-6Al-4V (AMS-T-9046A), and the intermediate layers were annealed Kovar® (Fe-29Ni-17Co). The metal-ceramic samples were actively brazed with Incusil®ABA (Ag-27.25Cu-12.5In-1.25Ti, 75 µm thick, from Morgan Technical Ceramics - Wesgo Metals) at 730ºC for 10-20 minutes in vacuum. Copper sheet (grade 101/102, 125-250 µm thick) was placed between each material prior to brazing.

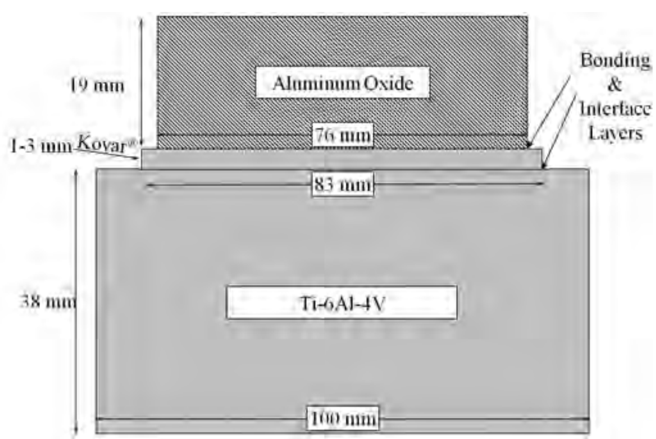

Figure 1: Single ceramic-metal active brazing samples

Subsequent ceramic-metal samples were fabricated in an attempt to meet two goals: thinner titanium backing plates and multiple aluminum oxide tiles brazed to a single titanium backing plate. The multiple tile assemblies were brazed with four square aluminum oxide tiles in a square array on a single piece of titanium (Fig. 2). Copper sheets were placed between each tile prior to the active brazing cycle.

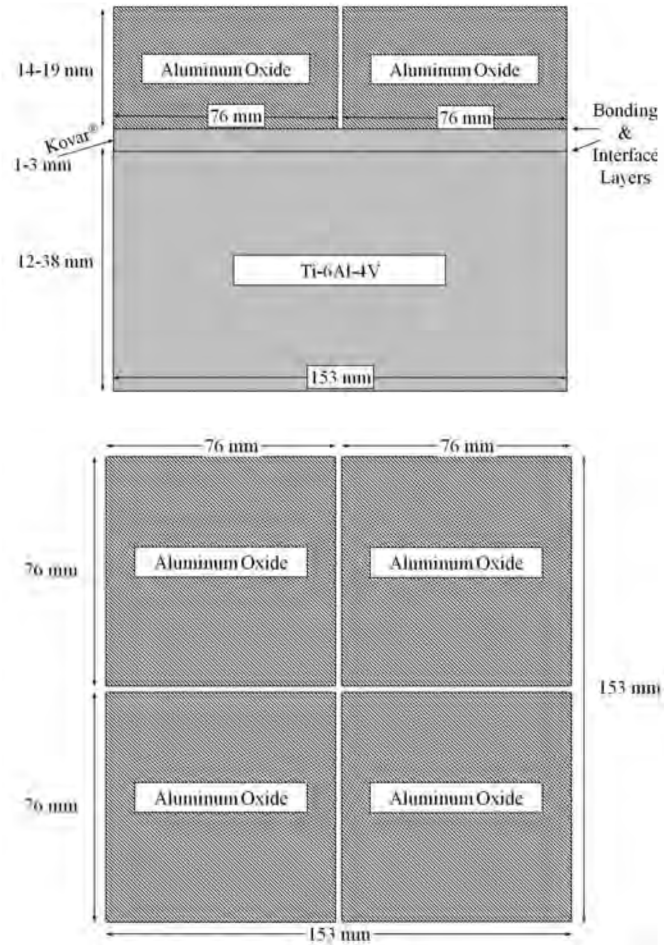

Figure 2: Top: Side view of multi-tile ceramic-metal active brazing samples. Bottom: Top view of active brazing samples.

Pyramidal core metallic sandwich panels were considered as a lightweight interface/backing layer. Metallic sandwich panels with 1.5 mm thick Kovar® facesheets and a 316L stainless steel (316L SS) core were manufactured by Cellular Materials International Inc. (Charlottesville, VA). The sandwich panels (Fig. 3) were fabricated by laser spot welding with a core relative density of 4.0% and an overall thickness of 23 mm.

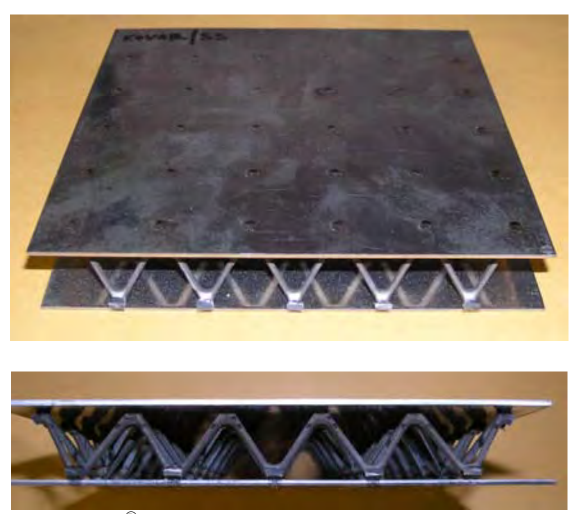

Figure 3: Kovar® /316L SS pyramidal core sandwich panels

The final demonstration of the active brazing technology on a large multi-tile ceramic-metal array was performed at Solar Atmospheres Inc. (Souderton, PA). The final dimensions of the large multi-tile ceramic metal array were 610 mm x 610 mm containing 49 whole (19 mm x 76 mm x 76 mm) and 7 half (19 mm x 38 mm x 76 mm) aluminum oxide tiles.

Results

This effort was initiated in an attempt to create a strong bond between a ceramic tile and a lightweight high strength metal. Aluminum oxide and titanium (Ti-6Al-4V) were excellent candidate materials not only because of their mechanical properties (high strength, low density, etc.), but because of their similar coefficients of thermal expansion. Individual aluminum oxide-titanium samples were fabricated via active metal brazing in a range of geometries. Variations included the addition of a Kovar® cover plate in a range of thicknesses, Kovar® intermediate layers in a range of thicknesses, and copper interlayers in a range of thicknesses. An example of one of these samples is shown in Fig. 4 with a Kovar® cover plate and a hot pressed aluminum oxide ceramic tile. All of these combinations were successful in creating sound brazed samples as long as a Kovar® intermediate layer and copper interlayers were used while the titanium backing plate was thick. All samples kept a consistent 38 mm thick titanium backing plate. The resulting product was extremely heavy and the next goal was a lighter weight option by actively brazing a single aluminum oxide tile to a titanium backing plate with a thickness of roughly 7 mm. Many combinations of cover plate and Kovar® intermediate layers were attempted; however, no ceramic-metal samples survived the brazing process without cracking the ceramic tile. Copper mesh interlayers were inserted for plastic deformation purposes, but none of these samples survived processing. Examination of the failures led to the conclusion that all of the lighter samples were failing in bending and only a more rigid backing plate structure would be able to accommodate the stresses associated with the cool-down from active brazing temperatures. Initial trials with the Kovar®/316L SS pyramidal core sandwich panel backing plates were extremely successful. The active brazing process created sound bonds between aluminum oxide, copper, and Kovar® while the weight of the Kovar®/316L SS pyramidal core panel was roughly equivalent to the goal of using 7 mm of titanium. Attempts to create even lighter ceramic-metal samples were successful, such as the aluminum oxide-Kovar®-titanium pyramidal core samples shown in Fig. 5.

Figure 4: Example of a single tile actively brazed ceramic-metal sample with thick titanium backing.

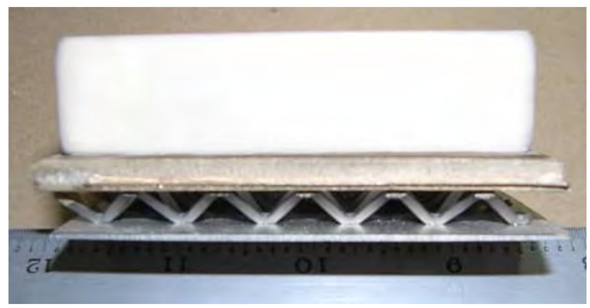

Figure 5: Example of a lightweight single tile actively brazed ceramic-metal sample with titanium pyramidal core backing.

Following the success in creating lightweight single tile ceramic-metal samples, the focus shifted to the subsequent goal of producing large multi-tile ceramic-metal arrays via active metal brazing. The first scale-up step was up to a four-tile square array shown in Fig. 2. Again, processing of four-tile square arrays was successful when a pyramidal core structure was used as the backing layer. A variety of possible geometries were demonstrated including with/without a Kovar® coverplate in a range of thicknesses, copper interlayers in a range of thicknesses, and Kovar® intermediate layers in a range of thicknesses. Examples of some of the brazed four-tile array samples are presented in Figs. 6 and 7. Attempts to use pyramidal core sandwich panels with lower relative core densities were unsuccessful (Fig. 8), with struts of the core buckling causing a failure of the overall ceramic-metal structure by bending. This was evidence of the severe stress/strain accommodated within the structures during cool-down.

Figure 6: Example of a four-tile actively brazed ceramic-metal sample with Kovar®/316L SS pyramidal core backing.

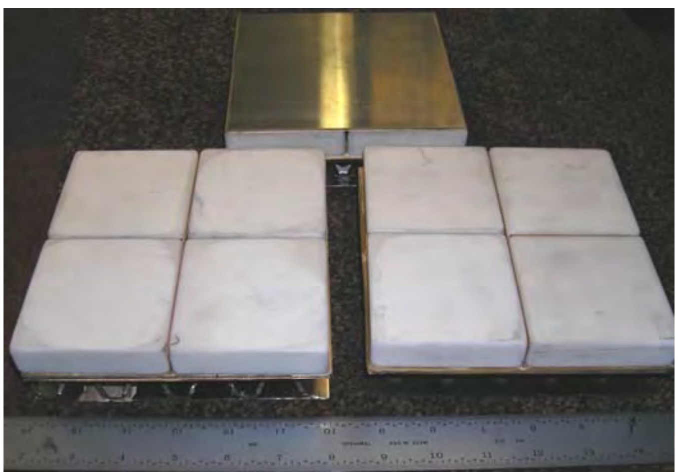

Figure 7: Example of four-tile actively brazed ceramic-metal samples with Kovar®/316L SS pyramidal core backing.

Figure 8: Unsuccessful four-tile actively brazed ceramic-metal sample with a lower core density pyramidal core backing.

The most robust design from the four-tile array ceramic-metal samples was chosen to scale-up to a full-size multi-tile panel. This design included 19 mm x 76 mm x 76 mm aluminum oxide ceramic tiles, two 250 μm thick copper sheets, a 3 mm thick Kovar® layer, and a backing sandwich panel with 1.5 mm thick Kovar® facesheets and a 316L SS core all brazed with Incusil-ABA. This was one of the slightly heavier designs; however, it was chosen with the additional intermediate and compliant layers (Kovar® and copper) to account for additional stresses associated with scale-up to the much larger panel. The final demonstration of the active brazing technology on a large multi-tile ceramic-metal array performed at Solar Atmospheres Inc. required some modifications from the single and four-tile samples fabricated in our laboratory vacuum furnace. A trial run demonstrated that additional time was required to compensate for the extra thermal load which added significant lag time to the active brazing cycle. This trend was verified with thermocouples in contact with the ceramics. The active brazing of the final multi-tile sample (Fig. 9) was a success with excellent bonding of all of the tiles to the metallic backing.

Figure 9: Images of large multi-tile array of aluminum oxide tiles actively brazed to Kovar®/316L SS pyramidal core backing using copper and Kovar® interlayers.

Discussion

Strong bonding between ceramics and metals using active metal brazing has been demonstrated successfully by many researchers; however, much of that work has focused on bond areas less than 1000 mm^2. When the ceramic-metal bonding area increases, the challenges associated with the escalating stress/strain from differential CTE between ceramic and metal grow tremendously. In fabricating single tile aluminum oxide thick titanium actively brazed samples, the use of copper and Kovar® interlayers was sufficient to accommodate the CTE mismatch and create strong, sound bonds. The 38 mm thick titanium back plate provided adequate global stiffness to minimize sample bending to allow nearly flat ceramic-metal samples following active brazing.

When attempting to fabricate thinner (lighter) ceramic-metal combinations, it was evident that a reduction in global stiffness of the backing allowed bending of the samples during cool down, causing premature failure (cracking) of the ceramic. Metallic sandwich panels consisting of solid Kovar® face sheets and a low density 316L SS pyramidal core proved to be a successful backing (or intermediate) layer to provide substantial specific stiffness. This sandwich panel material combination provided excellent ductility and low CTE face sheets. A sandwich panel with higher strength materials could be used; however, manufacturing the periodic structure would be more difficult. Also, the most important property that the sandwich panel brought to the ceramic-metal structure was specific stiffness, not strength. Attempts to use a lower density core demonstrated that there was a lower limit where the individual truss elements within the core were thinned and were unable to handle the stresses associated with the brazing process (see Fig. 8). In this case, a higher strength material for the core may be beneficial, but the weight reduction will be minimal since the core is typically less than 5% dense and is not a substantial part of the overall structure weight.

The demonstration of single tile ceramic-metal brazed laminates was encouraging, but to create full-scale structures it was necessary to fabricate multi-tile arrays. Initial four-tile array experiments quickly suggested the importance of global stiffness, especially as the sample surface area increased. The metallic sandwich panels proved to be the perfect combination of lightweight structure and global stiffness. Four-tile aluminum oxide arrays fabricated with the Kovar®/316L SS pyramidal core backing panel and copper/Kovar® interlayers exhibited sound bonds and nearly flat samples following the active brazing process. In order to fabricate more sizable arrays, a larger vacuum furnace than that available in our laboratory was required. In addition to demonstrating scale-up, this exercise of using the vacuum brazing/heat treating facilities at Solar Atmospheres also showed the robustness of the sample design and the processing route.

Future options to create even lighter ceramic-metal active brazed structures include lower density materials for the pyramidal core backing layers, such as titanium. Other sandwich panel configurations (honeycombs, foams, etc.) could provide the required specific stiffness at a lower cost and should be considered. Further optimization could also include the minimization of the copper and Kovar® interlayers. This future exercise could greatly benefit from modeling to supplement the design and processing work. Only cursory mechanical testing was completed with inconsistent results. Future optimization work should include extensive mechanical testing to not only achieve enhanced bonding strength, but to better understand the relationship between bonding area and bond strength.

Conclusions

- Demonstrated success in actively brazing individual (76 mm x 76 mm) aluminum oxide ceramic tiles to 38 mm thick titanium backing plates when using copper and Kovar® intermediate layers.
- In order to create lighter ceramic/metal brazed structures, metallic sandwich panels (Kovar® facesheets and a 316L SS pyramidal core) were required as a backing layer to both increase global bending rigidity and to accommodate the stress/strain associated with the cool-down from brazing temperatures.
- Successfully scaled-up first to four-tile and finally to a 610 mm x 610 mm multi-tile array of actively brazed aluminum oxide on a Kovar® / 316L SS pyramidal core sandwich panel backing plate.
- Demonstrated a viable route to fabricate large arrays of aluminum oxide ceramic tiles actively brazed to a lightweight engineered metallic backing with excellent specific properties.

References

[1] Zaera, R., Sanchez-Saez, S., Perez-Castellanos, J.L., and Navarro, C. "Modelling of the adhesive layer in mixed ceramic/metal armours subjected to impact," *Composites (A)*, Vol. 31, No. 8 (2000), pp. 823-833, 2000.

[2] Mizuhara, H. and Mally, K. "Ceramic-to-Metal Joining with Active Brazing Filler Metal," *Welding Journal*, Vol. 64, No. 10 (1985), pp. 27-32.

[3] Mizuhara, H. and Heubel, E. "Joining Ceramic to Metal with Ductile Active Filler Metal," *Welding Journal*, Vol. 65, No. 10 (1985), pp. 43-51.

[4] Gibson, L. and Ashby, M., Cellular Solids-Structure and Properties, Second edition. Cambridge University Press, (New York, 1998).

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