IV.E.6 Low-Cost, High-Temperature Recuperators for SOFC Fabricated from Titanium Aluminum Carbide (Ti_2AlC)

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Objectives

- Verify technical feasibility of solid oxide fuel cell (SOFC) recuperators made of titanium aluminum carbide (Ti_2AlC) through analysis and testing.
- Develop and validate fabrication approach for SOFC recuperators using Ti_2AlC.
- Establish limited-run production capability for SOFC recuperators for systems of 3 to 10 kW net power.

Accomplishments

Initial work in a Phase I small business innovative research (SBIR) project has resulted in the following accomplishments.

- Tested a recuperator core sample, demonstrating suitability of Ti_2AlC for this application.
- Demonstrated feasibility for key manufacturing issues: molding of fins with sufficiently thin dimensions, bonding of components for final assembly, and cost estimates for fabrication consistent with recuperator cost targets.
- Sized recuperator for SOFC system of target power level (3-10 kW).

Introduction

Achieving low system cost for SOFC technology requires novel approaches to the materials used for the air preheat recuperator. The recuperator is needed to heat up large quantities of air (~6 to 7 times in excess of stoichiometric requirements). The cost of existing recuperator designs is high primarily because of the high cost of the materials used. Heat resistant metal alloys tolerant of gas temperatures up to 1,000°C such as the Inconel-series metal alloys are typically used. These alloys are expensive, difficult to machine and form, and cannot be cast into near-net shape, leading to bulky heat exchanger designs. Further, the recuperator surfaces exposed to air need to be aluminized to prevent chromia poisoning of the cathode. The aluminizing further increases cost.

A new class of machinable, easily fabricated ceramic materials with good high temperature properties has been discovered. The example of this material class that is best suited for the recuperator application is Ti_2AlC. This material has excellent high temperature mechanical and thermal properties, high temperature stability, and good manufacturability, making this an ideal material for high temperature recuperators, specifically for air preheaters for SOFCs. Extensive testing has been carried out by our subcontractor in environments similar to that of a SOFC recuperator to provide assurance that the material is compatible with this application. The material forms a strong protective alumina layer which adheres well to the base material because of the very close match between the coefficients of thermal expansion of alumina and Ti_2AlC.

Fabrication with Ti_2AlC involves the following steps: preparation of a powder of the material, combining with organic binders, heating to a modest temperature level, injection molding, cooldown, soaking in water to partially dissolve the binders, and sintering at high temperature (and perhaps simultaneously joining separately molded parts). Follow-up processing can include machining and subsequent joining.

Approach

TIAX is developing an approach for net-shape (or near net-shape) fabrication of SOFC recuperators with machinable ceramic (Ti_2AlC) using counterflow plate-fin heat exchanger configurations. During the Phase I work, we first assessed key manufacturability attributes of the material and our design approach, including molding of thin fins, bonding of component parts of a Ti_2AlC recuperator, and estimated cost for volume production. A small proof-of-concept recuperator core sample was designed, fabricated, and successfully tested. Testing included heat transfer performance testing and thermal cycling. Analysis was carried out for sizing of a full-scale recuperator for a 3 to 10 kW SOFC system.

Results

Manufacturability test work included mold experiments to verify that fins with sufficiently thin dimensions can be fabricated, tests of diffusion bonding of pre-sintered parts, and tests of simultaneous diffusion bonding and sintering.

Small fin dimensions will enable high heat transfer performance with a compact lightweight recuperator. Fins of thickness from 0.5 to 2 mm were fabricated using a dedicated mold. Examples of the molded fins are shown in Figure 1. The molding and sintering work showed that fins with optimized dimensions can be fabricated using this approach.

The ability to use diffusion bonding to connect Ti_2AlC parts makes fabrication of complex structures much easier and eliminates the use of a separate bonding material, whose compatibility with the SOFC recuperator environment would have to be proven. Bond testing was carried out first for presintered parts machined to mimic fins and a plate to which the fins would be attached with connection between the fin tips and the plate. The parts bonded securely with no evidence of gaps at the bond interfaces. Additional work was carried out with unsintered parts to test simultaneous sintering and bonding. Two parts bonded in this fashion are shown in Figure 2. The high level of continuity of the material across the interface of the formerly separated parts shows the success of this joining technique.

Testing was carried out with a proof-of-concept core sample of the Ti_2AlC recuperator. The core sample is shown in Figure 3. The sample was machined out of a block of Ti_2AlC, and hence has somewhat coarser

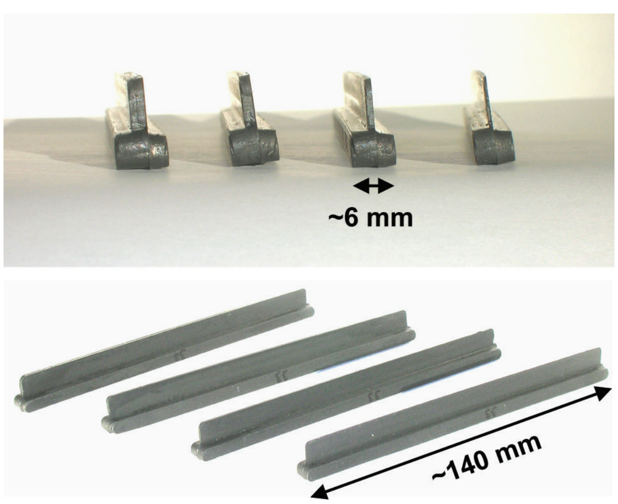
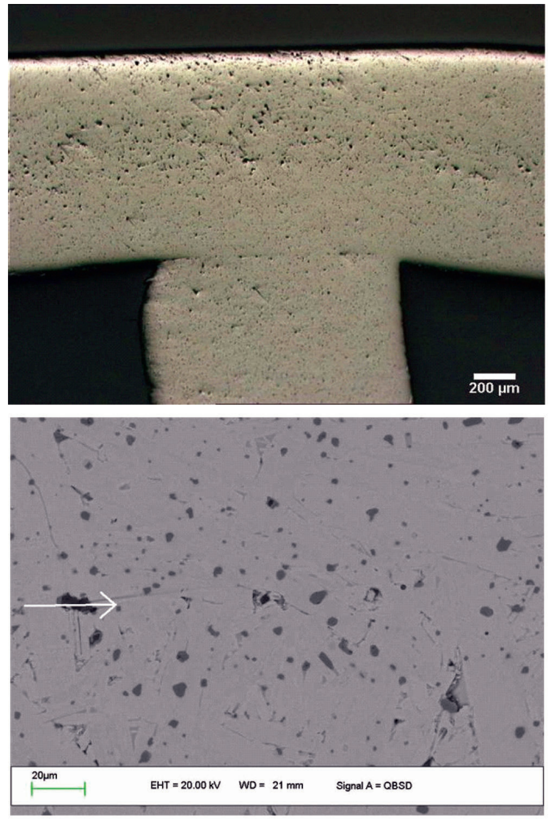


FIGURE 1. Molded Fins Prior to Sintering



Arrow shows location of pre-bonding part boundary

FIGURE 2. Closeup and Scanning Electron Microscope Image of Simultaneously Sintered and Bonded Ti_2AlC

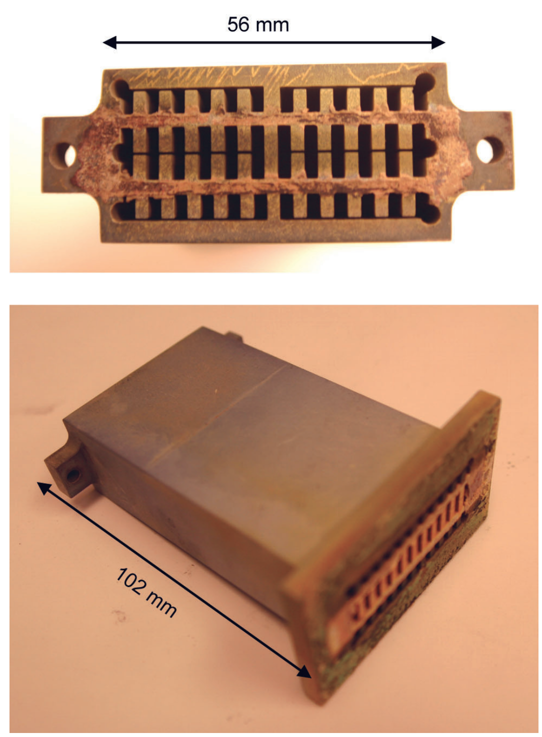


FIGURE 3. Recuperator Core Sample after Testing

dimensions than desired for a full-scale recuperator and plain fins, rather than enhanced fins which will be implemented in a more mature design. The core sample is intended to represent a portion of a recuperator in that it does not provide the full level of effectiveness required for the SOFC application. Roughly four of these sections in series would be required to achieve the desired level of recuperator effectiveness. Testing was carried out with the core sample representing a different portion of a complete counterflow recuperator for each test. Air inlet temperatures were selected accordingly. Test results for one of the tests are shown in Figure 4. The effectiveness measured for the core sample ranged from roughly 40% to 60%, with lower effectiveness for the lower test temperatures. The results compared well with predicted effectiveness levels for the lower test temperatures and exceeded the predictions at higher temperatures.

Transient testing was also carried out with the core sample to determine whether the material is susceptible to thermal gradients and thermal shock. The core was heated up to a high temperature with the hot gas inlet temperature close to 1,000°C and then allowed to cool. Tests were done with peak cooldown rates for measured air temperatures up to 45°C/min. Total test time for the core sample, including both steady-state performance tests and transient tests, was 67 hours. The sample showed no indications of damage after testing.

Analysis was carried out to design a recuperator for the SBIR Topic Description requirements, which were as follows.

- Pressure drop:
  - 6 to 10 in w.c. (1.5 to 2.5 kPa) on the air side
  - 3 to 5 in w.c. (0.75 to 1.25 kPa) on the stack exhaust side
- Effectiveness: 85% to 90%
- Flow rate: 1,500 standard liters/min (53 std ft^3/min or 108 kg/hr)

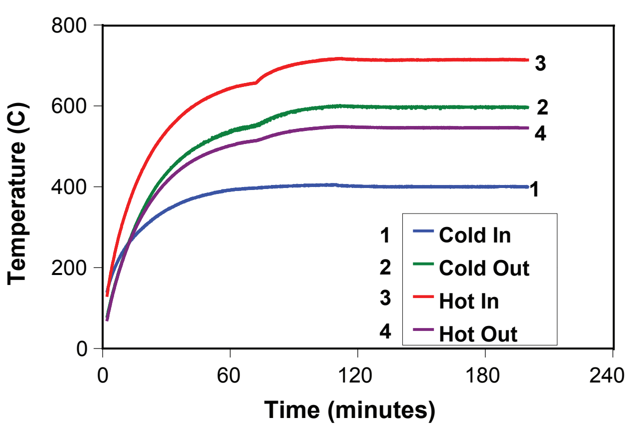


FIGURE 4. Example Data for Core Sample Testing

Based on these parameters, the recuperator uninsulated size including manifold passages is 15 inches long x 6 inches wide x 7 inches high. Its weight is roughly 25 lb (11.4 kg). Manufacturing cost analysis was carried out for the recuperator design for a production volume of 50,000 units per year for a production process which has been proposed but must be validated in the next phase of the work. The analysis made use of TIAX's activity-based manufacturing cost analysis tools, used extensively for a wide range of products from appliances to fuel cells (e.g. Reference 1). The cost calculated for the recuperator is roughly $200, 58% of which represents raw material costs. This is based on a future cost scenario for titanium powder, one of the key raw materials. The assumed cost scenario is consistent with predictions of References 2 and 3.

Conclusions and Future Directions

The work carried out during the Phase I SBIR project supports the feasibility of the proposed approach for manufacture of low-cost, high-performance recuperators for SOFC fuel cells using Ti_2AlC. Two of the key manufacturing issues have been tested with subscale fabrication tests. A proof-of-concept recuperator core sample was fabricated and successfully tested. Thermal and manufacturing cost analyses were carried out, thus defining the size of a recuperator for SOFCs in the 3 to 10 kW range and showing that the recuperators can be low-cost in volume production.

Next steps will include verification of full-scale manufacturing and a series of environmental tests for the Ti_2AlC material to assure compatibility with the SOFC exhaust gas in the anticipated recuperator operating environment. The work will lead towards fabrication and testing of a full-scale recuperator prototype and set up for limited production of the prototype after successful testing.

FY 2007 Publications/Presentations

1. SBIR Phase I final presentation made to DOE/NETL project management, March 20, 2007.

2. SBIR Phase I final report has been finalized and will be submitted in July 2007.

References

1. "Conceptual Design of POX / SOFC 5kW Net System", presentation to DOE/NETL, prepared by Arthur D. Little, Inc., January 2001.

2. Crowley, G., "Low-Cost Titanium", *Advanced Materials & Processes,* November 2003.

3. Camanoe Associates, "The Role of Titanium in the Automobile: Understanding the Economic Implication of Three Emerging Technologies", report prepared for the Northwest Alliance for Transportation Technology, July 2002.