Development of micro-column arrays (MCAs) for thermal management of spacecraft environments

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ABSTRACT—A technology for the successful fabrication of micro-column arrays (MCAs) has been developed. MCAs consist of densely packed micro-cones separated by cone-shaped micro-cavities. These structures have been fabricated on several types of metal foil samples and exhibit low reflectance (<0.171) and high absorptance (>0.978) over a wide spectral range in a very close approximation of blackbody behavior. The purpose of this project was to exploit the near-blackbody nature of the MCA structures for providing heat acquisition and/or heat rejection (thermal management) of spacecraft and space station components and environments. The project allowed continuation of the fabrication and characterization of the MCA samples based on selected metal foils that are of interest to NASA/JSC. It permitted focus on understanding how the fabrication conditions, as well as any post-fabrication processes (i.e., etching, coating), affect the reflectance and absorptance of the MCA structures. More important, it permitted extension of a successfully tested transmission line matrix (TLM) simulation model to radiative heat transfer processes (dissipation and collection).

GOALS OF THE PROJECT

Miniature and effective temperature control systems are critical in a variety of applications, including space exploration, where weight, volume, and reliability are extremely important. Complex processes are currently used to manage heat fluxes generated from various sources. In addition, different surfaces have to be controlled separately and maintained at different temperatures. Micro-column arrays (MCAs) have been fabricated by a pulsed laser modification process on various materials, including Si, SiC, refractory metals, stainless steels, and high-temperature ceramics.[1] MCA-structured surfaces increasing the specific area more than 10 times are currently used for drastic improvement of bonding between very dissimilar materials.[2] The goal of this project is to explore the use of MCA structures on metal foils for heat acquisition and/or heat rejection through their near-blackbody nature.

RESULTS

Initial FEM modeling indicated that MCAs are very effective heat reducers compared to smooth metal surfaces. Shown in Figure 1 is an FEM analysis of the temperature under a fixed heat flux of bare SiC and a SiC MCA. A 13.5 percent reduction in temperature was realized. In space applications, payload volume and weight are important design parameters. From that perspective, Ti has the lowest density (4.5g/cm^3) when compared to other materials from which we have made

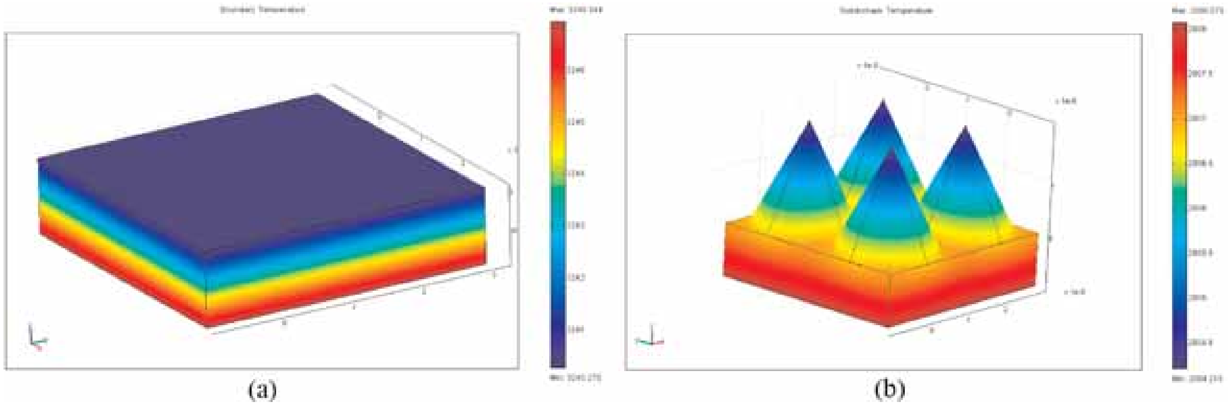
(a)
(b)

Figure 1. Finite element method simulation of the steady state temperature under a constant heat flux ($5x10^6$ W/m^2) for (a) un-structured and (b) MCA-structured silicon carbide. The MCA sample has a 13.5% lower temperature.

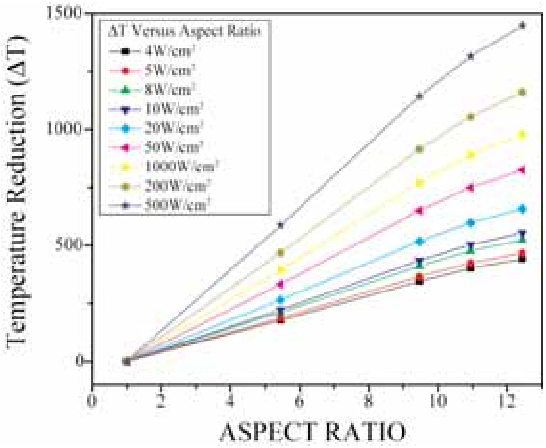

Figure 2. Simulations carried out on the MCA model of different aspect ratios fabricated on Ti, showing temperature reduction of the base for a wide range of heat fluxes at different aspect ratios. Saturation due to surface-to-surface radiation occurs for an aspect ratio ~12.

MCA, such as tantalum (16.4g/cm^3), Hastelloy C276 (8.94g/cm^3), and alloy321 (7.92g/cm^3). Additionally, Ti is more stable in space and extreme environments than other lightweight metals such as aluminum. As a result, we have used Ti as the base material for further FEM analysis.

For a given density of MCA, the crucial simulation parameter that determines the amount of heat loss is the structure's aspect ratio. This can be defined as the ratio of the total extended surface area to the base area. Since heat loss through radiation is proportional to the area of the emitting surface, a large aspect ratio leads to increased heat loss from the MCA. At high aspect ratios, however, the increased surface area is offset by increased surface-to-surface radiation between individual columns. This is illustrated by Figure 2, which shows the temperature of titanium MCA with different aspect ratios for a variety of heat fluxes. The saturation of the heat loss begins near an aspect ratio of 12. This knowledge will allow us to predict the heat loss behavior of the MCA so that we can tailor the structures for different applications in addition to providing optimal geometry information for refining the MCA formation process.

The need for lightweight, high-performance thermal management systems is moving from the traditional military and aerospace applications into industrial and consumer electronics as ever-increasing speeds in ever-smaller devices calls for the use of new materials. Metal matrix composites such as aluminum, silicon carbide, ceramics and aluminum nitride, and graphite structures such as pyrolytic graphite and foamed graphite are all being used to improve thermal performance without adding weight. Beyond conventional brazing, furnaceless bonding based on self-igniting foils serving as localized heat sources is unique, as it facilitates formation of a high-performance thermal joint between dissimilar high-temperature metal and ceramic materials. Such joints offer approximately 10 times the thermal conductivity of thermal epoxies along with the ability to bond in air, without the use of fluxes, and to have a bond that allows rework of damaged parts. Specific application areas include defense, space, avionics, laser systems, and high-performance computers.

Our goal was development of novel, ultra-strong, high-temperature bonding of titanium (Ti) to ceramic materials through application of advanced nano- and micro-scale structures based on MCAs fabricated by pulsed laser ablation. The proposed manufacturing process proceeded from recent innovations on the enhancement of bond strength using surface modification of adherent surfaces and modification of adhesives by the introduction of reinforcing components.

The advanced features of the MCA-structured surfaces that

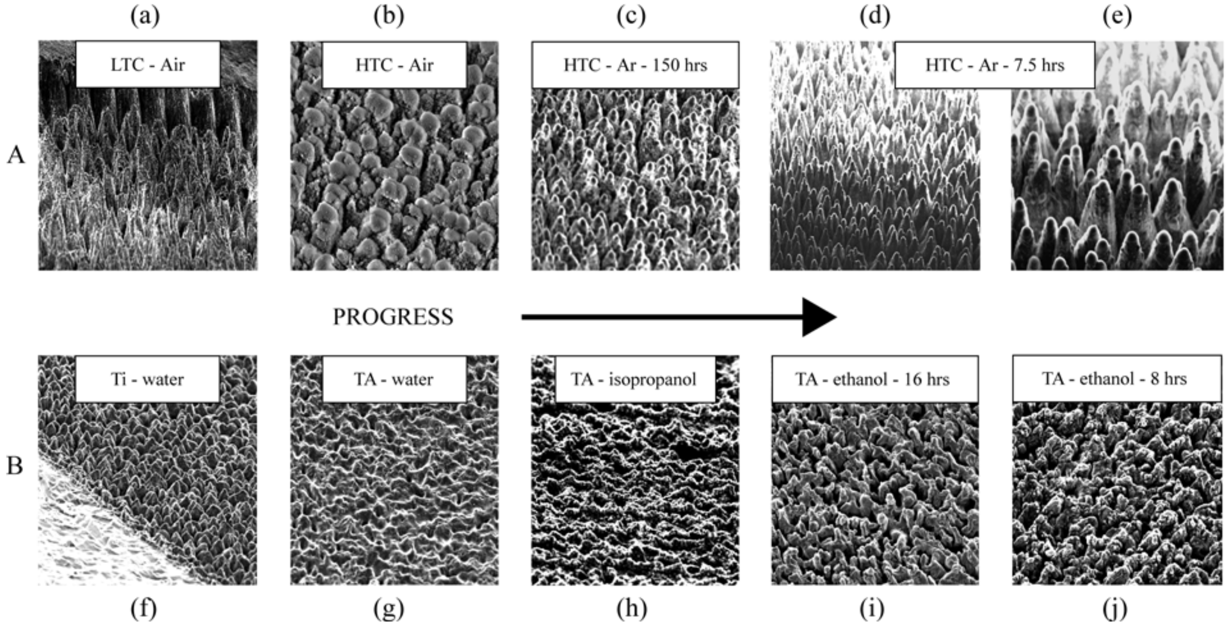

Figure 3. Optimization of the MCA fabrication process on HTC (a-e) and TA (f-g)

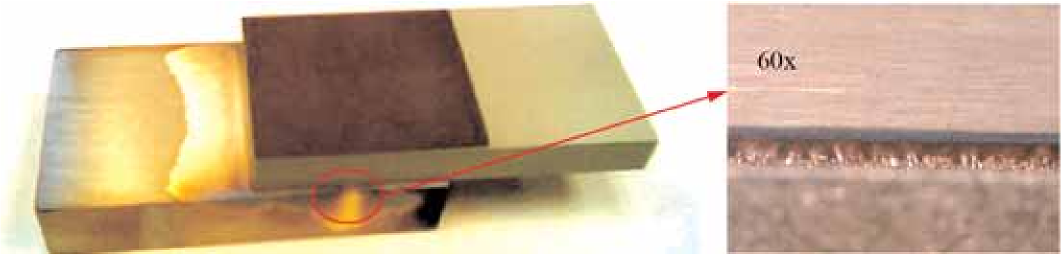

Figure 4. Titanium alloy coupon brazed to an HTC coupon using a conventional brazing furnace

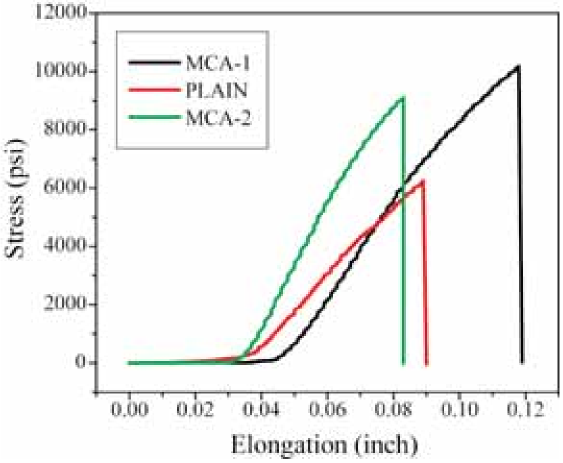

Figure 5. Stress-elongation graph showing bond strength for a plain sample versus two MCA-structured samples (~53% average increase)

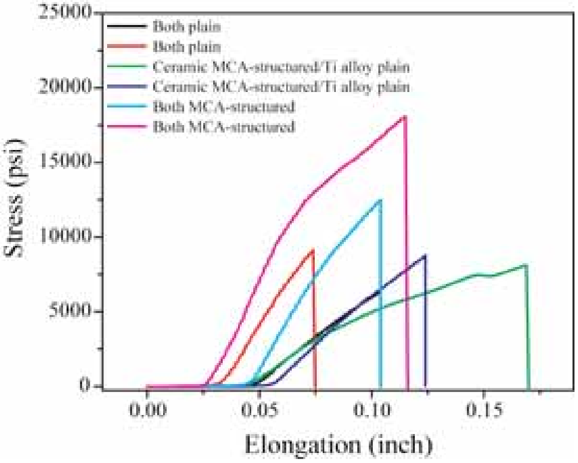

Figure 6. Stress-elongation graph showing bond strength for samples with only one surface structured versus ones with two MCA-structured surfaces (up to ~90% increase)

contribute to the strength and stability of the brazed joints are: (i) interlocking of the braze material between micro columns; (ii) more than 10-fold increase in the specific surface area; (iii) inherent elasticity of the micro cones that could compensate for the difference in thermal expansion between the Ti alloy, ceramic, and the braze material or under shear stresses; (iv) repeated bend contours of the surface, which prevent hydrothermal failure; (v) improved wettability.

The experimental work was directed toward improvement of the bond strength between Ti alloy (TA) and high-temperature ceramic (HTC) widely used in several military and space applications. Optimization of the MCA fabrication process to accomplish the outlined goal was carried out in several ways, including: a) development and implementation of a LabView-based software interface to control the XYZ sample stage during laser fabrication in an efficient manner; b) transfer of the MCA fabrication parameters from previously developed for low-temperature ceramic (LTC) and Ti to those applicable for HTC and advanced Ti alloys, respectively; c) optimization of the ambient for processing high-temperature ceramic and advanced Ti alloy; d) preliminary optimization of the laser-scanning scheme in order to minimize the total exposure time.

Such optimization was needed due to substantial differences in the chemical composition among these materials resulting in higher melting temperatures, thermal conductivity, and changes in optical characteristics. Figure 3a and 3b show SEM images from samples illustrating the progress on the transfer of the MCA fabrication process from low temperature to high temperature ceramic (a) and from Ti to advanced Ti alloys, respectively, through optimization of the process ambient and scanning parameters. In order to efficiently process the high temperature ceramic, the ambient was changed from air to argon and the processing time was reduced from 150 hours to 7.5 hours for processing of 1 square inch. For processing of the advanced Ti alloy, the ambient was changed from water to ethanol and the processing time was reduced from 16 hours to 8 hours per square inch. In both cases the transfer was accomplished by choosing an ambient with a lower thermal conductivity and decreasing the number of scans while increasing the translation speed.

Conventional brazing of MCA-structured and unstructured advanced Ti alloy and HTC coupons in a single lap configuration (Figure 4) was performed in a conventional vacuum tube furnace. The results achieved from testing of these samples (Figure 5) indicate an average 53 percent increase in bond strength when using the MCA structuring. Another set of single lap-bonded samples was tested in order to verify whether fabrication of MCA on both high-temperature ceramic and Ti alloy surfaces is affecting the overall bond properties. The results shown in Figure 6 indicate a dramatic increase (up to 90 percent) in bond strength when both high-temperature ceramic and Ti alloy coupon surfaces are structured.

A different type of bonding based on self-igniting foils is currently being developed in collaboration with Integrated

Micro Sensors, Inc. and a large aerospace company. It is expected that fabrication of MCA on ceramic surfaces would significantly improve the wettability during the pre-brazing, necessary for the advanced bonding process. In addition, the MCA formation can possibly reduce formation of intermetallic compounds that greatly decrease the strength of the bonds between metal and ceramics.

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