Development of Micro Column Arrays (MCA) for Thermal Management Applications

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ABSTRACT—Micro Column Arrays (MCA) have been formed on thin metal foils, selected ceramics, and semiconductor materials. The formation process by pulsed laser ablation is being refined to produce MCA structures tailored for different applications. Such applications of MCA include: possible passive cooling components which would collect or remove heat by radiative absorption or emission though their near-blackbody nature, electronics based on field emitters, and enhancement of bond strength between similar or dissimilar materials. Results on the bonding of various metallic and ceramic plates with various epoxies indicated an increase of up to four times in the bonding strength for joints that employed MCA versus the ones without.

THERMAL MANagement of spacecraft and space station environments is an important issue in both manned and unmanned exploration of space. Typical active systems based on large, liquid-based heat exchange systems add extra weight to the spacecraft and rely on mechanical components which can malfunction, thus affecting maximum payloads and the lifetime of a mission. A possible alternative is a passive cooling system in which thin coatings or foils would collect or remove heat by radiative absorption or emission. In order for a radiation-based system to be feasible, the foil or coating would have a high emissivity and/or absorptance. Additionally, newer materials based on metal matrix composites like aluminum silicon carbide, ceramics like silicon carbide and aluminum nitride, and graphite structures with the characteristics of pyrolytic graphite and foamed graphite are all being used to improve thermal performance without adding weight. However, there are strength and stability issues when trying to integrate these materials with standard structural materials.

A technology for the successful fabrication of Micro Column Arrays (MCA) on various materials has recently been developed in conjunction with Integrated Micro Sensors, Inc. (IMS) of Houston, Texas. MCAs consist of densely packed micro cones separated by cone-shaped micro cavities. They exhibit low reflectance (<0.171) and high absorptance (>0.978) over a wide spectral range in a very close approximation of blackbody behavior.[1] Employment of MCA is expected to enhance the strength and stability between materials due, in part, to a large increase in the effective surface area of the bond joint.

This project seeks to explore MCA structures from thin foils as a possible passive cooling system which would collect or remove heat by radiative absorption or emission though their near-blackbody nature. Also under investigation is the bonding of advanced thermal and structural materials to one another.

Methodology

MCAs are produced by pulsed laser ablation of the substrate material combined with mechanical translation of the sample to create cone-shaped micro tips interdigitated with cone-shaped micro cavities.[2,3] The formation of the cone-shaped micro columns protruding above the surface by about 10-20 μm is a result of redistribution of the surface material which is made molten by ablation with a sufficiently long sequence of laser pulses. The most important parameter in this process is the laser fluence, which should provide heating near or slightly above the solid melting threshold. The second parameter is the number of laser shots applied to the same surface spot, which should exceed a threshold value (>103). For this project, MCA have been investigated on *SiC*, *Si*, *Ta*, *Ti*, *Ti*-alloys, ceramics, and stainless steel materials. An example of the effect on the number of shots and the laser power is shown in Fig. 1 for fabrication of MCA on silicon.

For bond strength enhancement investigations, fabrication of MCA on *Ti/Ti* alloys and various ceramics was performed.

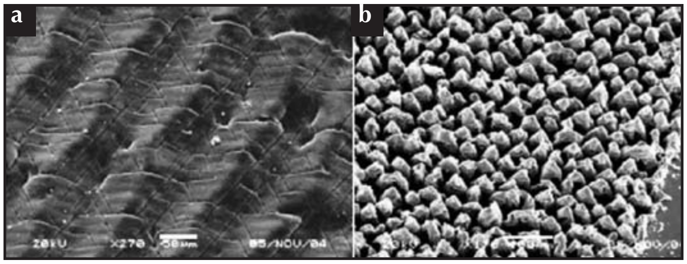

Figure 1. Effects of the laser fluence and number of laser shots on MCA fabrication on silicon: (a) 2400 shots, 23 J/cm^2 ; (b) 3200 shots, 32 J/cm^2.

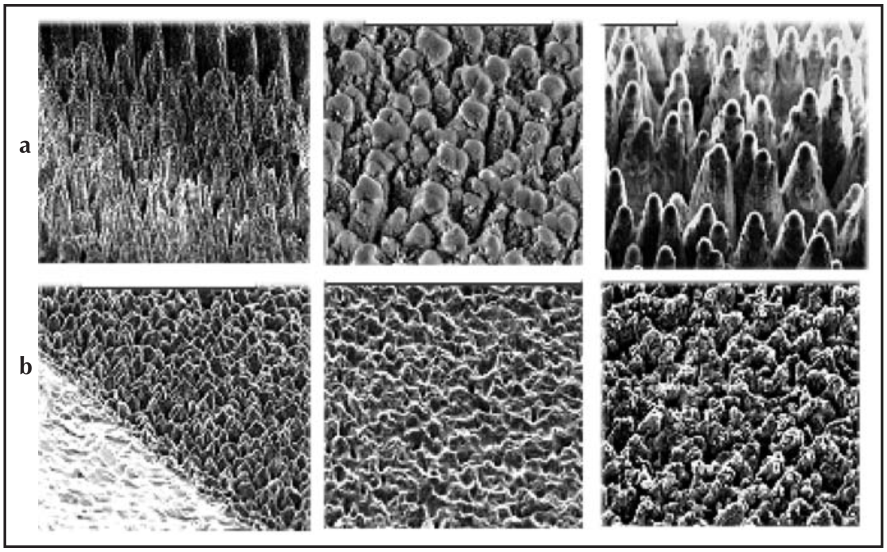

Figure 2. SEM images showing the progress of MCA parameter optimization on ceramics and *Ti*-based materials. (a) parameters optimized for traditional ceramic -> traditional ceramic parameters used on high strength ceramic -> optimized parameters for high strength ceramics; (b) optimized for *Ti* -> *Ti* parameters used *Ti* alloy -> optimized parameters for *Ti* alloy.

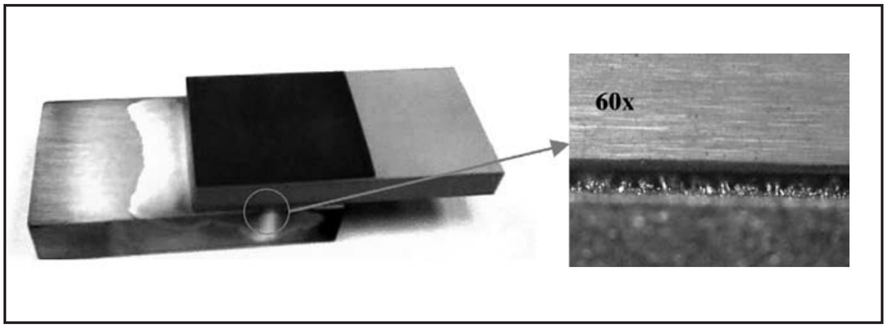

Figure 3. Titanium alloy coupon brazed to a high-strength ceramic coupon using a conventional brazing furnace.

These materials are widely used in military and space applications. Conventional brazing of MCA-structured and unstructured *Ti* alloy and ceramic coupons was performed in a vacuum tube furnace and the resulting coupons tested for bond strength in a single lap configuration.

Equipment

A Baasel LBI 6000 Nd:YAG Laser (Ï = 1064 nm) and a NEAT computer-controlled XYZ Stage have been used to fabricate MCA structures from several semiconductor and metal materials. In addition to this stage, we have implemented a small processing chamber accessory for the laser which will provide pumping to low vacuum, or purging with various gases such as dry air or with an inert gas, such as nitrogen or argon. We have also built a small liquid pumped cuvette for laser ablation of the samples in liquids (water, ethanol, methanol). The chamber or the cuvette can be displaced under the laser beam by the same computer-driven X-Y-Z stage as used for in-air processing.

Results and Discussion

A majority of the activity on this project has been to optimize MCA formation on the *Ti*/*Ti* alloys and on several relevant ceramic materials. This involved transfer of the MCA fabrication parameters previously developed for traditional ceramics and *Ti* metal to those applicable to the alloys under consideration. Significantly different parameters were needed because of the substantial differences in the chemical composition between these materials resulting in higher melting temperatures, thermal conductivity and changes in optical characteristics. Figure 2a and 2b show SEM images from samples illustrating the progress on the transfer of the MCA fabrication process from a ceramic to a reinforced ceramic sample (a) and from *Ti* to *Ti*-alloy (b), respectively, through optimization of the process ambient and scanning parameters.

Figure 3 is an example of a finished single lap test coupon, consisting of a *Ti*-alloy plate brazed to a ceramic plate, both of which have been MCA processed. Similar coupons, along with non-MCA textured structures, were tested for bond strength. The results achieved from testing of these samples (Fig. 4) indicate an average of about 53 percent increase in the bond strength when using the MCA structuring. The advanced features of the MCA-structured surfaces that contribute to the strength and stability of the brazed joints are: (1) the interlocking of the braze material between micro columns, (2) a more than a 10-fold increase in the specific surface area, (3) the inherent elasticity of the micro cones that could compensate for the difference in thermal expansion or for the shear stresses between the bonded materials and the braze material, (4) the repeated bend contours of the surface preventing hydrothermal failure, (5) the improved wettability of the surfaces by the braze material.

There are several advantages of the MCA process over other optical coating technologies and surface treatments. In theory, generation of the MCA structures can be accomplished directly on the surface of virtually any material, including flexible materials, metal foils, plastic films, and on surfaces with a complex shape. The coatings are robust with long-life and can either resemble the

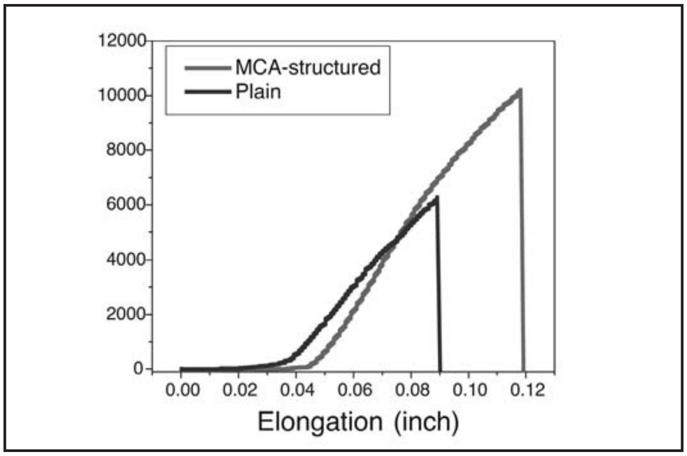

Figure 4. Stress-Elongation graph showing bond strength for a plain sample versus a MCA-structured sample (~ 53% average increase).

properties of the base material or can be automatically coated with the base material oxide. Finally, the MCA fabrication process is environmentally safe and low cost with high scalability.

Conclusions

Micro column arrays exhibiting low reflectance, high emissivity, and large effective surface areas have been fabricated by pulsed laser ablation on several metals, ceramics, and semiconductor materials. In addition to its use for emissive-based thermal management, MCA can produce enhanced bonding and brazing strength when used for either identical or dissimilar materials. By testing samples of non-textured and MCA processed metal to ceramic braze joints, we have achieved an approximately 50 percent increase in strength when MCA are present. Some of the specific applications that can benefit from this and other aspects of MCA technology include space, defense, avionics, laser systems, and high-performance computers.

References

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Presentations

Starikov, D., N. Medelci, S. Paranjape, F. Attia, B. Eranezhuth, C. Joseph, and A. Bensaoula. "Enhanced Metal-Ceramic Brazed Bond Strength Using Micro/Nano Structured Surfaces and Nanofoil Technologies," Material Science and Technology Conference 2007 (MS&T'07®). Sept. 16–20, 2007, Detroit, MI. (*submitted*).

Funding and Proposals

Starikov, D. "A Novel Manufacturing Process for Ultrastrong, Intelligent Adhesive Bonds," NSF-NIRT, $450,000 (CAM/IMS; *declined*).

Starikov, D. "Ultra-Strong High-Temperature Bonding of Titanium to Ceramic Materials," DOD (MDA), (IMS/CAM; Phase I *funded* $100,000; Phase II *approved*).

Starikov, D. "Universal Method of Bonding Steel Repairs to Aluminum Structures," Air Force Phase I SBIR, $100,000 (IMS/CAM; *submitted*).

LASER SYSTEM—Sujay Paranjape, master's student in mechanical engineering, studies methods for bonding metallic materials for lightweight space-based cooling systems in the UH Center for Advanced Materials. Parnjape earned his bachelor's degree in mechanical engineering at Pune University in India.