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 and semiconductor materials. The formation process is being refined to produce MCA structures tailored for different applications. As a part of the optimization, Finite Element Method (FEM) simulations of MCA structures have been used to study the influence of the MCA geometry on the resulting heat loss. FEM modeling indicates that micro column arrays are very effective heat reducers compared to smooth metal surfaces. This finding has been experimentally verified by comparing the temperature of MCA-structured and identical non-structured metals under resistive heating.

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Thermal management of spacecraft and space station environments is an important issue in both manned and unmanned exploration of space. Transporting heat away from spacecraft components as well as bringing heat to other systems is often based on large, liquid-based heat exchange systems. Such active systems add extra weight to the spacecraft and rely on mechanical components which can malfunction, thus affecting the maximum payload and 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 to have emissivity and/or absorbtance.

Technology for the successful fabrication of Micro Column Arrays (MCA) on thin metal foils has recently been developed in conjunction with Integrated Micro Sensors, Inc. (IMS) of Houston, Texas. MCA consist of densely packed micro cones separated by cone-shaped micro cavities and exhibit low reflectance (< 0.171) and high absorbtance (> 0.978) over a wide spectral range in a very close approximation of blackbody behavior.[1]

This project seeks to explore MCA structures from thin foils as possible passive cooling systems which would collect or remove heat by radiative absorption or emission though their near-blackbody nature. The study involves the formation and characterization of MCA samples as well as modeling of MCA sample performance though numerical simulation.

Methodology

MCA 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 cone-shaped micro-columns protruding above the surface by about 10-20 μm is a result of redistribution of the surface material 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 close 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 between 10^3 and 10^4. For this project, MCA have been investigated on *SiC*, *Si*, *Ta*, *Ti*, and stainless steel materials.

We undertook computer simulation of MCA thermal properties in order to better understand the effect of MCA geometry—in particular, the aspect ratios—on heat loss properties. The thermal analysis was carried out using Comsol FemLab 1 software, which is an environment for modeling and solving engineering problems that are based on partial differential equations (PDEs). The built-in physics models allow definition of physical parameters such as material properties, loads, constraints, sources, and fluxes, without defining the underlying equations. The software has several different modules, one of them being the heat transfer module, which has been used throughout this simulation and supports fundamental heat transfer mechanisms such as conduction, convection, and radiation. For radiative heat transfer, the software includes models for both surface-to-surface radiation and surface-to-ambient radiation.

Equipment

A Baasel LBI 6000 Nd:YAG Laser (λ = 1064 nm) and a NEAT computer-controlled XYZ Stage have been used to fabricate

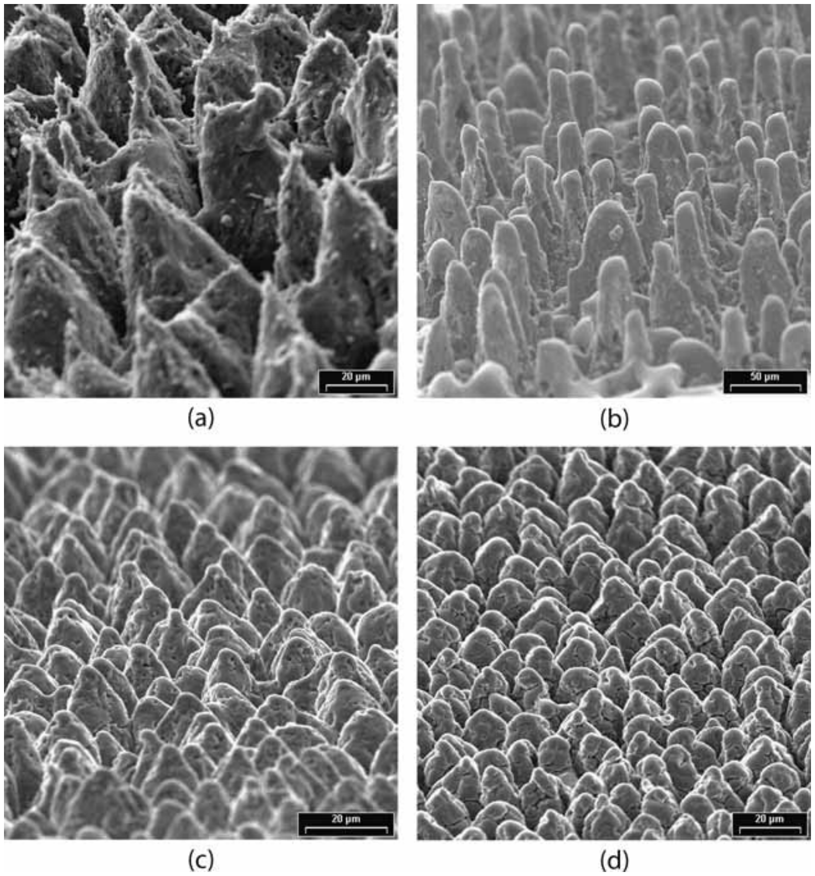

Figure 1. MCA samples fabricated in-house using an Nd:YAG laser. (a) and (b) are *Si* MCA under different processing conditions; (c) titanium; (d) stainless steel.

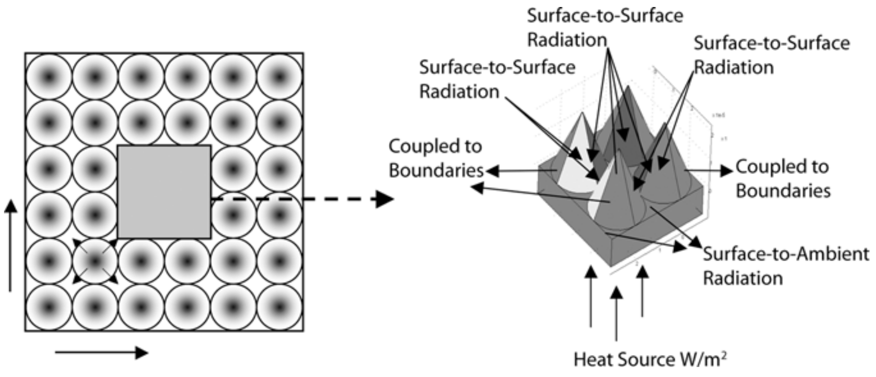

Figure 2. Schematic of an array of micro-cones modeling an actual surface with MCA. The view includes a 3D schematic describing the boundary conditions for the model, indicating surface-to-surface radiation and surface-to-ambient radiation boundaries.

MCA structures on several semiconductor and metal materials. In addition to the translation stage, we implemented a small processing chamber accessory, which will provide pumping to low vacuum or purging with various gases, such as dry air or 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 significant portion of activity on this project has been to translate MCA fabrication parameters developed with a *Cu* vapor laser system at our Russian collaborator's facilities to the Nd:YAG laser-based system we have in-house. To date, we have successfully fabricated MCA in-house on *Si*, *SiC*, *Ti*, *Ta*, and stainless steels, examples of which are shown in Fig. 1.

For the computer modeling, MCA samples were assumed to have uniform spacing and size with every micro-cone surrounded by eight other cones. In a vacuum environment, each cone radiates heat to the ambient, but a certain portion of the radiated heat will be re-radiated onto adjacent cones. In this manner, the cone contributes not only to cooling the base surface, but also heating the adjacent surfaces. The combined effect of the surface-to-ambient radiation and the surface-to-surface radiation determines the efficiency of the MCA in heat removal. Thus, a crucial simulation parameter is the aspect ratio of the structures which, for a constant MCA density, can be defined as the ratio of the total extended surface area to the base area.

A simple model consisting of a unit cell with four micro-cones interacting with each other was chosen for the simulations. The 3D diagram of the model with a more detailed picture for the unit cell is shown in Fig. 2. In all simulations, the base of the samples was supplied with a constant uniform heat flux. The ambient temperature was set to 0 Kelvin (considering space vacuum) and the sides of the base were assumed to be insulated. The base in our simulations has a 10 μm thickness, but the simulations are irrespective of this parameter since the calculated temperature is the final steady-state temperature and is, therefore, independent of the thermal conductivity based upon the assumption that the sides of the base are insulated.

The first set of simulations summarized in Fig. 3 compares the final steady state temperature of three 40 μm × 40 μm × 10 μm structures: a plain *Ti* sample (base only), a base with rectangular cross-section pin fins (for comparison purposes), and an MCA. The results of the simulation predict a substantial heat

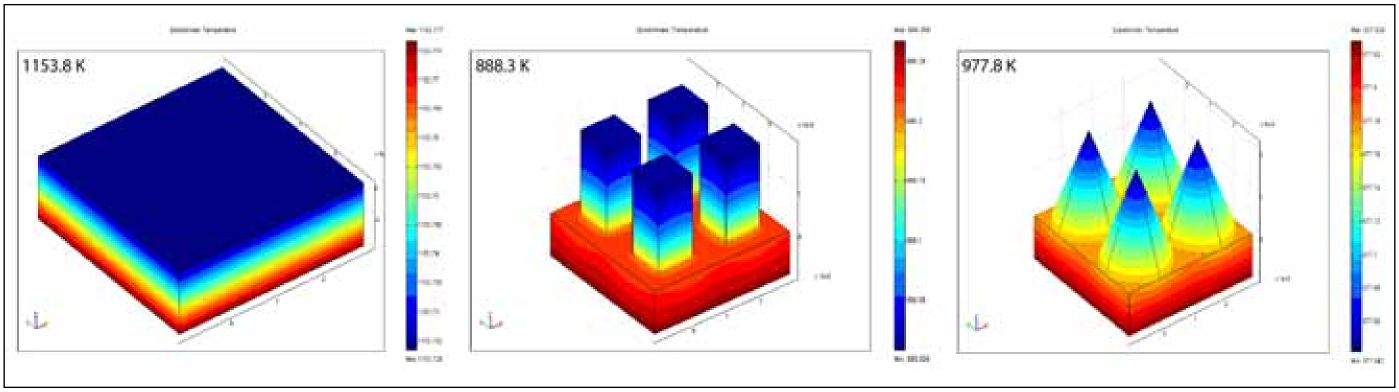

Figure 3. Simulations of different extended surface structures on a 40μ × 40μ surface of Titanium showing the individual steady-state temperatures when subjected to a heat flux of 4 W/cm^2, with temperature decrease of 176° based on MCA and 265° based on the rectangular cross-section pin fin arrays.

reduction of the *Ti* for MCA structured surfaces. Based on a heat flux of 4 W/cm^2, the steady state temperature of the plain *Ti* substrate was found to be 1153.8 K. The rectangular pin fins yielded a final temperature of 888.3K and the MCA a temperature to 977.8K, giving a temperature reduction of 265° for the pin fin model and 176° for the MCA model.

To determine the influence of MCA geometry on the cooling of the samples, a second set of simulations was undertaken in which various aspect ratios (AR) were used for the MCA geometry. The aspect ratios were calculated by taking the ratio of the total surface area of the MCA to the base area. This is achieved by increasing the cone height in the model. The results are detailed in Fig. 4 and show the steady state temperature variation as a function of input heat fluxes and aspect ratios. It is clear that higher aspect ratios result in better temperature reduction of the base surface in this model. A saturation regime is seen, however, for ratios greater than ~12. This is most likely a consequence of the dominant effect of the surface-to-surface heating component.

The temperature reduction predicted by our modeling has been experimentally verified. Two samples of a stainless steel alloy 321—one with fabricated MCA and one without—were resistively heated in a vacuum environment. The temperature at the center of each sample was measured by a thermocouple in contact with the back side. The temperature of the MCA-processed sample was approximately 20-25% lower for a wide range of input heat fluxes compared to the un-textured sample (Fig. 5). The results are surprisingly close to those predicted and are a clear demonstration of the predicted heat loss due to increased radiative emission of the MCA samples.

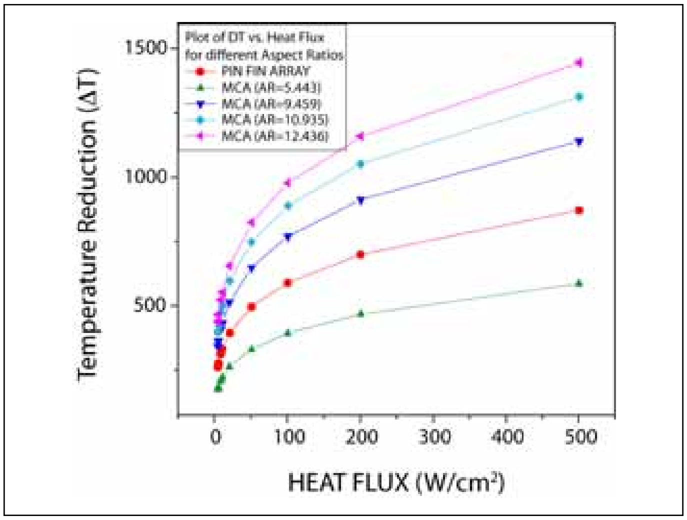

Figure 4. Simulations carried out on the MCA model for different aspect ratios on *Ti*, showing temperature reduction of the base for a wide range of heat fluxes at different aspect ratios.

Conclusions

Micro-column arrays exhibiting low reflectance and high emissivity have been fabricated by pulsed laser ablation on several metals and semiconductor materials. We performed computer modeling of the heat loss behavior of MCA structures compared to un-textured materials and predicted substantial temperature reduction for the MCA samples. This result was experimentally verified on actual MCA materials. Further simulations highlighted that the aspect ratio of the MCA was the critical parameter in predicting the amount of heat loss, with the higher aspect ratios exhibiting increased temperature reduction. Based on these results, we believe that control of the aspect ratio will allow the temperature reduction capabilities of MCA to be widely tuned to meet a variety of thermal management applications.

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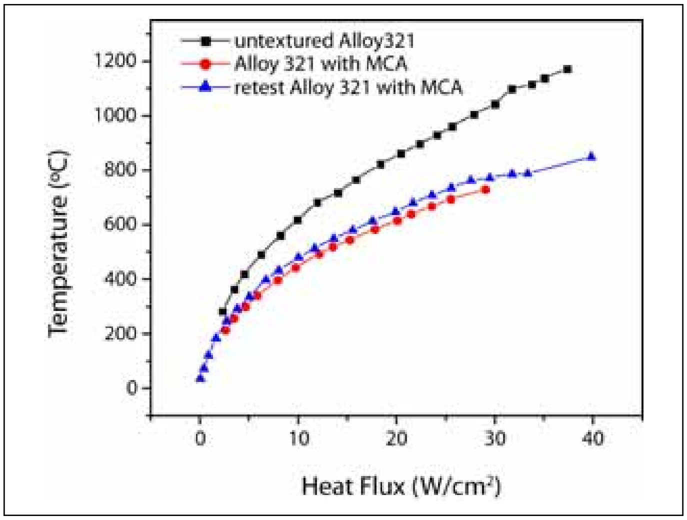

Figure 5. Temperature comparison between a stainless steel foil and MCA textured foil of the same dimensions under different heat fluxes. A reduction of 20-25% is seen between the two samples.

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Publications

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Presentations

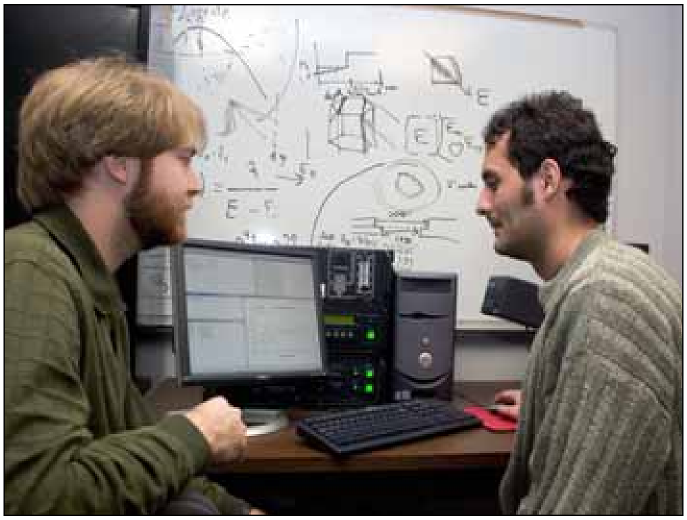
Bensaoula, A., D. Starikov, N. Badi, N. Medelci, R. Pillai, I. Rusakova, P. V. Kazakevich, A. V. Simakin, and G. A. Shafeev. "Influence of Laser Parameters on the Properties of Nanoparticles Produced by Laser Ablation of Solid Targets in a Liquid Environment," Second Conf. on Nanoscale Devices and System Integration, Houston, TX, April 4–6, 2005.

Funding and Proposals

"High-Reliability Low-Resistance Inexpensive Ohmic Contacts to *HgCdTe*," DoD (Army), IMS/CAM, $100,000. (*Not funded.*)

"Intelligent Ultra-Strong Adhesive Bonding of Dissimilar Materials," NASA, IMS/CAM, $70,000. (*Not funded.*)

"Ultra-Strong High-Temperature Bonding of Titanium to Ceramic Materials," DoD (MDA), IMS/CAM, $100,000.



ADVANCED MATERIALS—Dr. Chris Boney (*l.*), research scientist in physics, and Sidi Mohamed Behabib (*r.*), a researcher and exchange scholar from the University of Tlemcen in Algeria, operate a spectroscopic ellipsometry instrument. They look at optical properties to an index of a fraction to determine film thickness and alloy composition of heat samples. Their study focuses on how optical properties change at elevated temperatures.

REACTOR—Dr. Nacer Badi (*l.*), research assistant professor in physics, works with Rajeev Rajan Pillai (*r.*), at a multi-element coating reactor utilized for hardcoating MCA structures at the Center for Advanced Materials (CAM). Pillai is currently enrolled in the doctoral program in electrical and computer engineering.