Performance Life Testing of a Nanoscale Coating for Erosion and Corrosion Protection in Copper Microchannel Coolers

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ABSTRACT

High powered laser diodes, such as those used in materials processing and solid-state laser pumping, generate significant amounts of waste heat, which must be dissipated to maintain laser diode operating temperature. Typically, this waste heat is removed through the use of copper microchannel coolers (MCCs) wherein single-phase de-ionized water (DIW) coolant is pumped through the MCC at high flow rates. Though effective for cooling, high velocity, high purity, DIW leads to erosion-corrosion damage to the micro-scale internal heat transfer features of the MCC, raising the laser diode junction temperature, altering optical output, and limiting the useful lifetime of the diode. To prevent erosion-corrosion damage to copper MCCs and extend the service life of the laser diode assemblies, a nanoscale, conformal, hard, and inert coating has been developed that is applied using a vapor-phase deposition process to achieve a uniform coating on the high aspect internal features of the MCC. In this study, an extended life test is performed on stacks of four coated and four baseline uncoated copper MCCs subjected to operating conditions that simulate laser diode thermal management. Measurements of the DIW pressure loss across the MCC stacks and total MCC stack thermal resistance were taken over a range of flowrates at the onset of the life test and after approximately every 750 hours of exposure. After a total of 5210 hours of operation, it was observed that the thermal resistance of the baseline uncoated MCCs increased by around 30% from its initial value, while the thermal resistance of the coated MCCs varied by less than 10% from the initial value and was within experimental uncertainty. Additionally, a larger increase in pressure drop over time was observed for the baseline uncoated MCC stack than for the coated MCC stack. A theoretical investigation of the effect of a change in hydraulic diameter due to material removal by erosion-corrosion on the total thermal resistance of a microchannel cooler was performed. The results of this study support the conclusions that the increase in thermal resistance of the uncoated MCC stack is due to erosion-corrosion damage, and that the nanoscale coating provides effective protection from erosion-corrosion mechanisms that reduce MCC thermal performance.

KEY WORDS: Laser diode, thermal management, corrosion, erosion, microchannel coolers

NOMENCLATURE

c_p	Specific heat, J/kgK
D_h	Hydraulic diameter, μm
$\dot{m}$	Mass flow rate, kg/s
R_{th}	Thermal resistance, K/W
T	Temperature, K
u	Uncertainty, %
V	Volumetric flow rate, GPM

Greek symbols

ρ	Mass density, kg/m^3

Subscripts

H	Average heater
i	ith heater
in	Inlet
out	Outlet

INTRODUCTION

Laser diode arrays, or bars, with continuous wave (CW) output powers in the range of 50-100 W are used in a variety of applications including materials processing, medical applications, and solid-state laser pumping [1]. The electrical-to-optical efficiency of such diodes is typically 50-70% [2]. Therefore, a significant amount of waste heat is generated and must be dissipated in order to maintain the diode junction temperature within specified operating temperatures. Waste heat rejection is a key factor in the design of next generation laser diodes with increased output power and stable optical output; for every 3 K change in the laser diode junction temperature, the output wavelength is shifted by 1 nm. Due to the small footprint of the laser diode bars, the heat is dissipated at heat fluxes that can reach up to 1 kW/cm^2 [2].

The method most currently used for laser diode thermal management is through pumped single-phase cooling with microchannel coolers (MCCs). The MCCs contain micron-scale heat transfer features to encourage high convection heat transfer coefficients and increase the surface area for heat transfer. These MCCs are typically manufactured through the diffusion bonding of thin, individually photo-etched sheets of copper [3]. In a laser diode stack, the diodes are bonded directly to the MCCs, which are electrically connected in series to serve as electrodes for the diodes. Fig. 1 illustrates a typical MCC stack configuration [4]. To minimize leakage currents, the single-phase coolant must have a high electrical resistivity. High purity de-ionized water (DIW) with a resistivity of at least 0.3 MΩ·cm is a common coolant choice. The high linear velocity of the coolant through these channels causes a well-documented degradation mechanism known as erosion-corrosion, or flow-assisted corrosion [5]. Additionally, erosion-corrosion rates are exacerbated as the pH of the DIW decreases form pH 8 to 6. Eventually, erosion-corrosion damage to the internal heat transfer features of the MCC will degrade the thermal performance, requiring the MCC stack to be replaced. These frequent replacement can be very expensive and lead to significant system downtime.

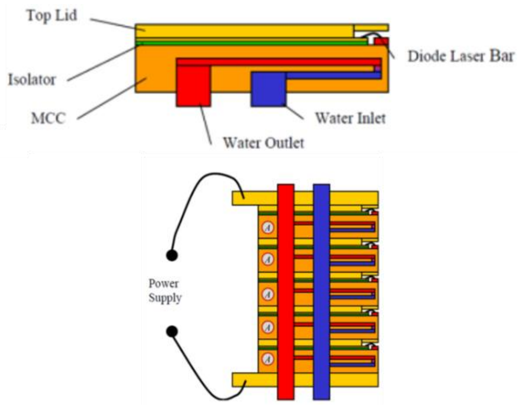

Fig. 1 Copper MCC stack used in laser diode thermal management with parallel cooling paths and series electrical connections [4].

The current state-of-the-art for reducing erosion-corrosion in copper MCCs is to apply a thin layer of nickel and gold plating to the internal features. However, this plating is known to be non-conformal and often contains pinholes which become nucleation sites for corrosion. Additionally, due to the high aspect ratio of the micron scale heat transfer features internal to the MCCs, attempts to produce a conformal nickel and gold plating can lead to blockage of the coolant passages.

In order to extend the lifetime of these copper MCCs, a nanometer thin, hard, inert, and conformal coating applied by a vapor phase deposition process has been developed. This coating provides erosion-corrosion protection to the high aspect-ratio internal features of copper MCCs used in laser diode thermal management [6,7]. To evaluate the effectiveness of this coating in prolonging the service life of copper MCCs, two sets of commercially available MCCs, one coated and one uncoated, were subjected to life tests and the thermal and hydraulic performance of each was measured over the course of 5000 hours of operation. Finally, a correlation based theoretical evaluation was performed to support the results of the life test.

COATING APPLICATION TECHNOLOGY

To extend the service life of copper MCCs used in laser diode thermal management, a vapor phase deposition process was developed to deposit a hard, inert coating on the high-aspect ratio internal features of the MCCs. This conformal and nanometer thin coating is designed to protect the underlying copper from erosion and corrosion damage without affecting the thermal or hydraulic performance of the MCC. Previous work has shown this coating to reduce corrosion rates of bare copper by up to two orders of magnitude over a wide range of DIW pH and dissolved oxygen (DO) content conditions [6]. Additionally, while the corrosion rate of bare copper varied widely over the different conditions, the reduced corrosion rate of the coated copper was consistent across all conditions [6]. Due to the nanometer scale coating thickness, the added thermal and hydraulic resistance is negligible, and has demonstrated a negligible effect on the performance of the MCC. The coating is applied in a deposition chamber where vapor phase reactants are dosed into the chamber. Deposition in the internal features of the MCCs is achieved by allowing enough time for the reactants to diffuse into the features. Currently, this process is limited to coating small batches of MCCs at a time. Work is ongoing to scale this process for large volumes of MCCs. Evaluations of coating thickness throughout the flow length of the MCC have demonstrated uniform coatings at a thickness of 100-200 nm in the high aspect ratio features of the MCC [6]. Thus, this method of deposition enables a uniform application of the coating throughout the MCC, providing erosion-corrosion protection and extending the life of the cooler.

MICROCHANNEL COOLER LIFE TEST EVALUATION

Experimental Setup

To evaluate the relative performance of coated and baseline uncoated copper MCCs, an experimental apparatus was designed and fabricated, which was used to measure the thermal and hydraulic performance of the MCCs under simulated laser diode thermal management operating conditions. An uncoated baseline MCC stack and coated MCC stack were evaluated simultaneously to provide an equivalent comparison of performance. Each stack consisted of four MCCs assembled in a parallel flow path. The test apparatus consisted of a pumped loop that provided each MCC stack with equal flow rates of DIW coolant. A schematic and photograph of the test apparatus are shown in Fig. 2 and Fig. 3, respectively. The experimental apparatus included components for monitoring and maintaining the resistivity, pH, and DO content of the DIW coolant within the ranges specified in Table 1.

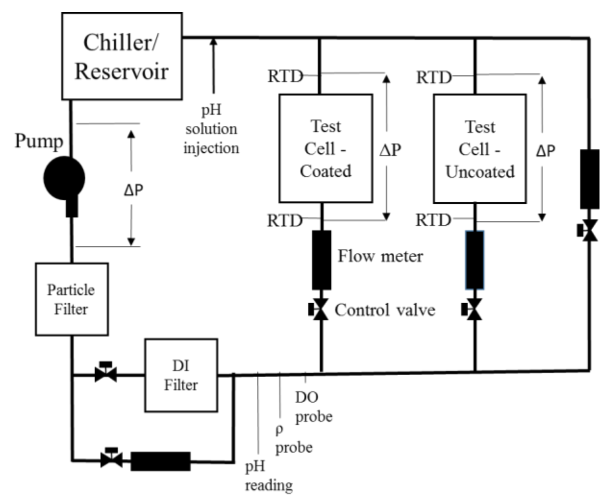

Fig. 2 Schematic of long term MCC life test apparatus [6]

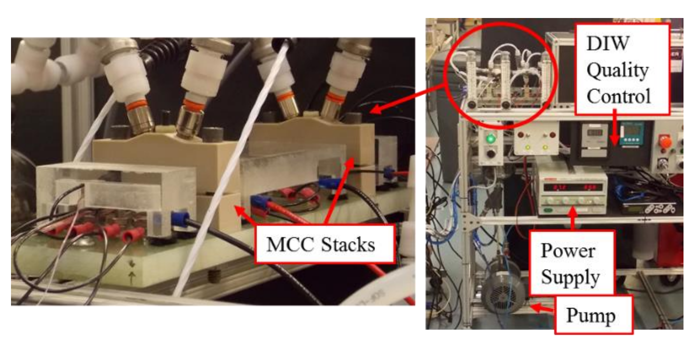

Fig. 3 Long term MCC life test apparatus [6]

Table 1. Long term MCC life test operating conditions

Operating Condition	Value
Coolant	De-ionized water (DIW)
Coolant resistivity	0.3 MΩ·cm ± 0.05 MΩ·cm
Coolant dissolved oxygen (DO)	10 ppm ± 5 ppm
Coolant pH	6 ± 1
Flow rate per stack	0.5 GPM
Coolant inlet temperature	18 - 25°C
Heater power supply voltage	90 VDC
Heater power supply current	6.8 A
Heater power per stack (per cooler)	324 W (81 W)

To simulate the waste heat load of the laser diodes, surface mount resistive heaters were soldered to the surface of the MCCs in the footprint of the laser diode and wired in parallel to assure an even distribution of applied power, assuming negligible difference in resistance between the heaters. Insulative layers were inserted between the MCCs to prevent heat leaks. Coolant manifolds were fabricated and installed to align the stack of four MCCs and deliver DIW coolant to the stacks. The location of the resistive heaters and an assembled MCC test stack are shown in Fig. 4.

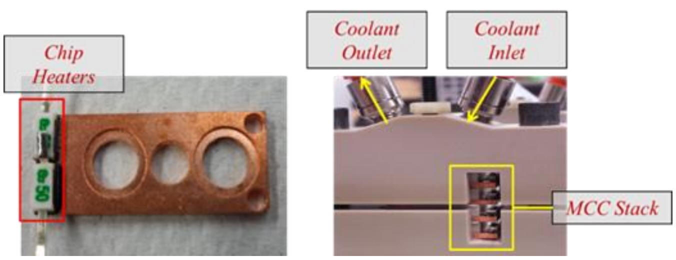

Fig. 4 Resistive heaters soldered to surface of copper MCCs to simulate laser diode waste heat (Left). Four MCCs integrated into a stack for life testing (Right). [6]

The test apparatus was instrumented to continuously measure several important parameters to characterize the thermal and hydraulic performance of the MCC stacks. The inlet and outlet temperature of the DIW for each MCC stack and the DIW pressure loss across each MCC stack were monitored for a constant flow rate of 0.5 gallons per minute (GPM) per stack. Thermocouples were attached to the surface of each MCC between the resistive heaters to measure the heater temperature of each MCC in both stacks. The total thermal resistance R_{th} of each MCC stack was calculated from Eq. 1 for an average stack heater temperature (T_H), DIW inlet temperature (T_{in}), DIW outlet temperature (T_{out}), DIW mass flow rate ($\dot{m}$), and DIW specific heat (c_p).

$$R_{th} = \frac{T_H - \left(\frac{T_{out} + T_{in}}{2}\right)}{\dot{m}c_p(T_{out} - T_{in})} \quad \text{Eq. 1}$$

The MCC stacks were operated continuously for over 5000 hours at the conditions listed in Table 1. At intervals of approximately 750 hours, a full characterization of the MCC stacks was performed over a range of DIW flow rates per stack (0.1 – 0.5 GPM) at a heater power of 221 W per stack. A lower heater power was used in these characterizations to prevent the resistive heaters from exceeding the maximum rated operating temperatures at the lower DIW flow rates.

Experimental Results and Discussion

The long term copper MCC life test was conducted for 5210 hours, with characterizations of the thermal and hydraulic performance of the MCCs occurring at the onset of testing (0 hours) and after 720, 1694, 2366, 3100, 3898, 4572, and 5210 hours of operation. The DIW pressure loss across the stacks at four of these time points is shown in Fig. 5 for the coated MCC stack for a range of flow rates. Similarly, Fig. 6 presents the DIW pressure loss across the baseline uncoated MCC stack. As expected, the pressure drop increases with increasing flow rate. In Fig. 7, the change in the pressure drop across the MCC stacks over the course of the life test is shown for a flow rate of 0.3 GPM, while Fig. 8 show the progression of pressure drop at a flow rate of 0.5 GPM throughout the duration of the life test. It can be seen that throughout the majority of the life test, the pressure drop is higher across the baseline uncoated stack than across the coated stack at the same flow rate. This is potentially due to a reduction in surface roughness in the MCC interior from the application of the coating. However, the pressure drop across the uncoated stack tends to decrease over the course of the life test, particularly at the higher flow rate. Meanwhile, the pressure loss across the coated stack decreased at a much lower rate. This is consistent with an increase in hydraulic diameter in the internal features of the uncoated cooler due to removal of material by erosion-corrosion processes.

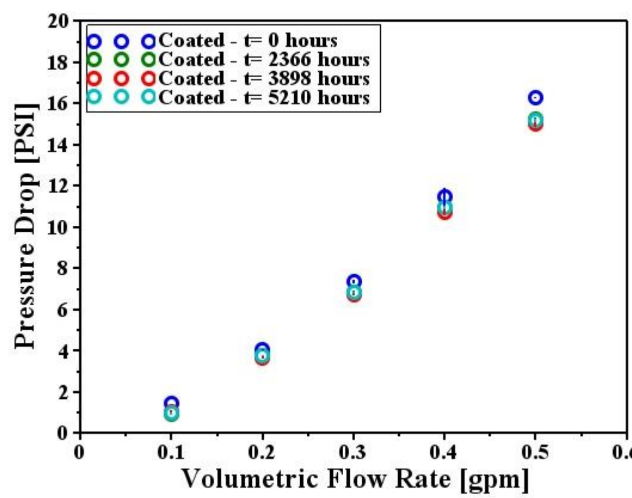

Fig. 5 DIW coolant pressure loss across the coated MCC stack over a range of flow rates at several life test time points

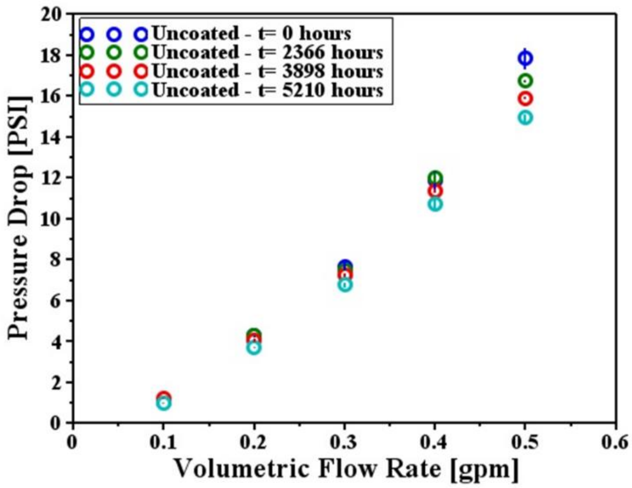

Fig. 6 DIW coolant pressure loss across the baseline uncoated MCC stack over a range of flow rates at several life test time points

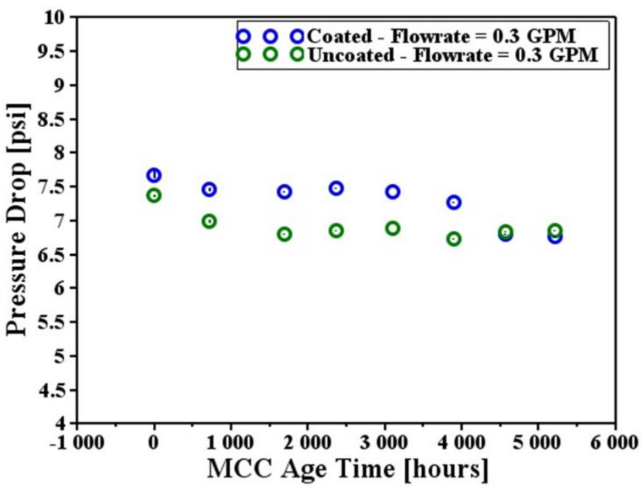

Fig. 7 Evolution of coolant pressure loss over test duration at a flow rate of 0.3 GPM

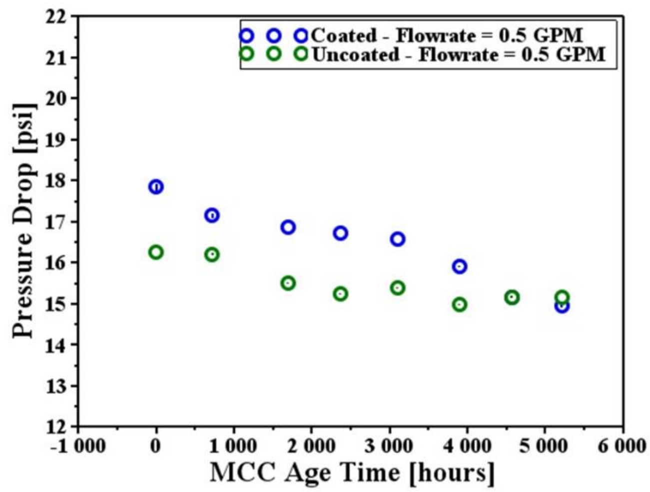

Fig. 8 Evolution of coolant pressure loss over test duration at a flow rate of 0.5 GPM

In addition to the pressure drop across the MCCs, the inlet and outlet temperatures of the DIW coolant were measured, as were the temperatures of the resistive heaters soldered to the surface of the MCCs. These temperatures were used to calculate the overall thermal resistance of the MCC stack from Eq. 1. The total thermal resistance of the uncoated baseline and coated MCC stack at four time points throughout the course of the life test over a range of DIW flow rates is shown in Fig. 9 and Fig. 10, respectively. As the DIW flow rate through the MCC stack increases, the thermal resistance is reduced due to increased convective heat transfer in the microscale internal features. In Fig. 11 and Fig. 12, the change in thermal resistance over the course of the life test is given for both stacks at flow rates of 0.3 GPM and 0.5 GPM, respectively. The error bars represent the uncertainty (±10-12%) in the calculation of the thermal resistance. The determination of this uncertainty is described in the next section. As is shown in these figures, the thermal resistance of the baseline uncoated MCC stack increases over time while the coated MCC stack maintains a consistent thermal resistance throughout the duration of the 5210 hour life test. The observation of decreasing pressure loss and increasing thermal resistance of the uncoated MCC stack is consistent with the removal of material due to erosion-corrosion processes occurring in the microscale internal features of the MCCs. As material is removed, the hydraulic diameter of the internal passages increases, reducing the Reynolds number of the DIW coolant flowing through the passages, and reducing the corresponding convective heat transfer coefficient. Conversely, the consistent pressure loss and thermal resistance of the coated MCC stack indicates that the applied nanoscale coating provides a protective barrier which minimizes erosion-corrosion damage to the internal features of the MCCs. To further illustrate the evolution of the thermal performance of the coated and baseline uncoated MCC stacks, the thermal resistance of the stacks is normalized to their initial values and plotted (without error bars) in Fig. 13 and Fig. 14 for DIW flow rates of 0.3 GPM and 0.5 GPM, respectively. At both flow rates, an increase in the thermal resistance of the baseline uncoated MCC stack of over 30% from the initial value is observed. On the other hand, the thermal resistance of the coated MCC stack is maintained with 10% of its initial value throughout the course of the life test.

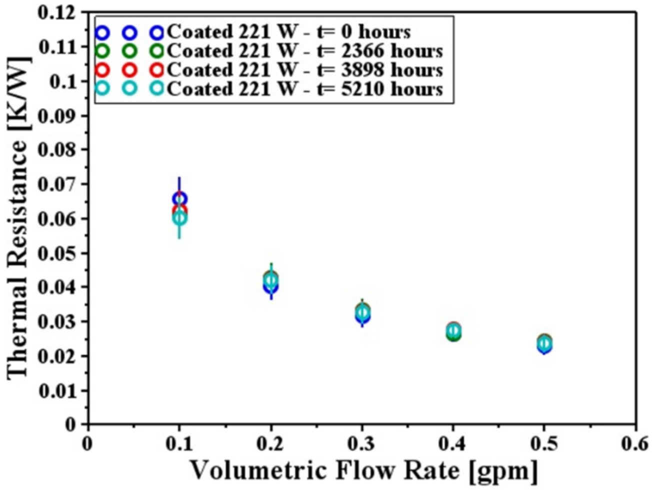

Fig. 9 Total thermal resistance of the coated MCC stack over a range of flow rates at several life test time points

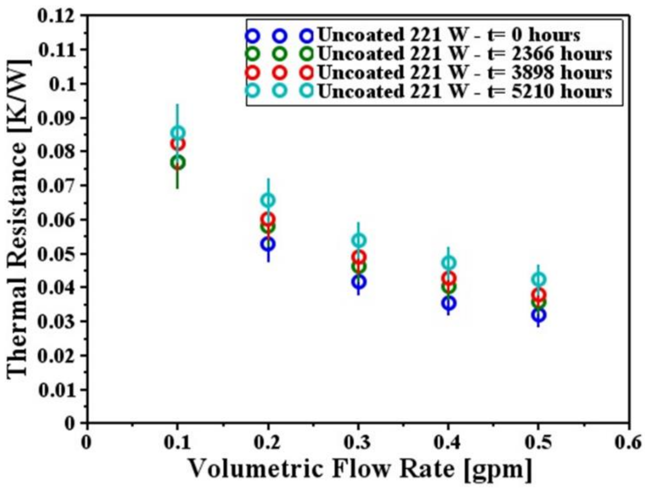

Fig. 10 Total thermal resistance of the baseline uncoated MCC stack over a range of flow rates at several life test time points

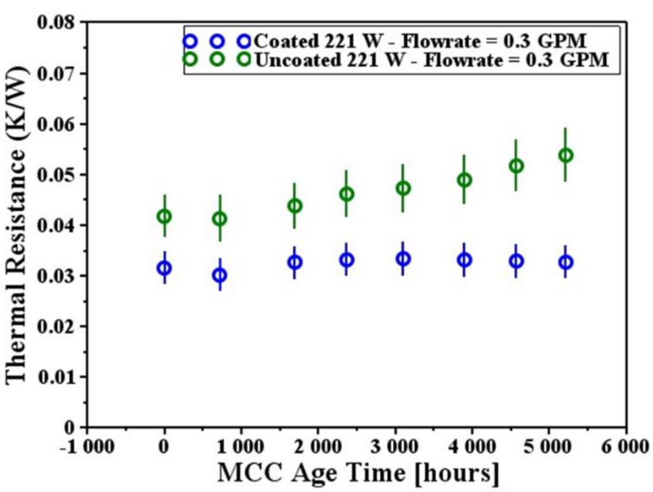

Fig. 11 Evolution of MCC stack thermal resistance over test duration at a flow rate of 0.3 GPM

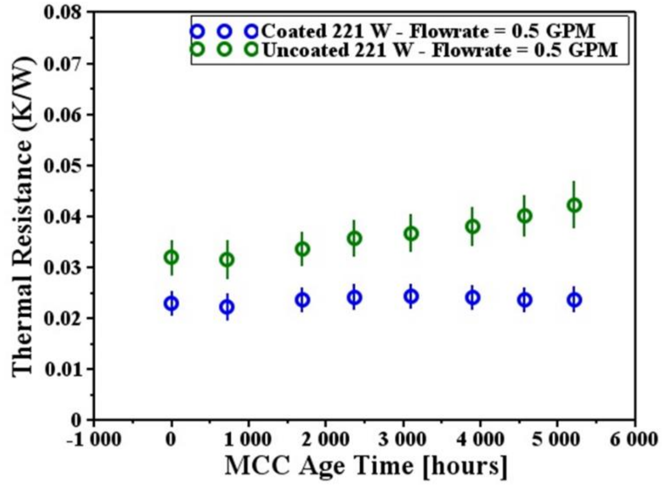

Fig. 12 Evolution of MCC stack thermal resistance of test duration at a flow rate of 0.5 GPM

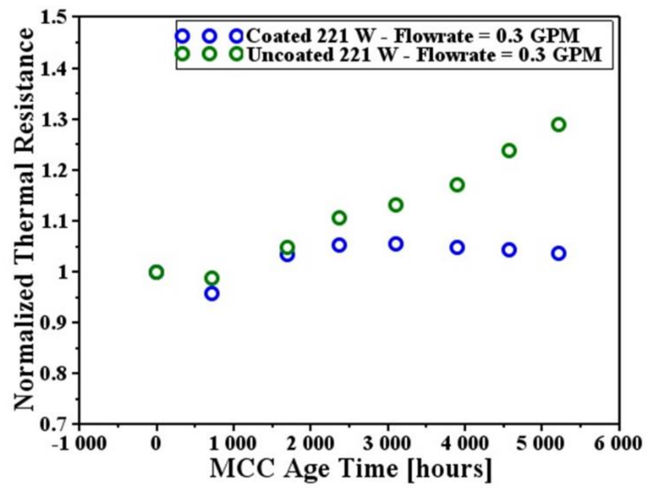

Fig. 13 Evolution of normalized MCC stack thermal resistance over test duration at a flow rate of 0.3 GPM

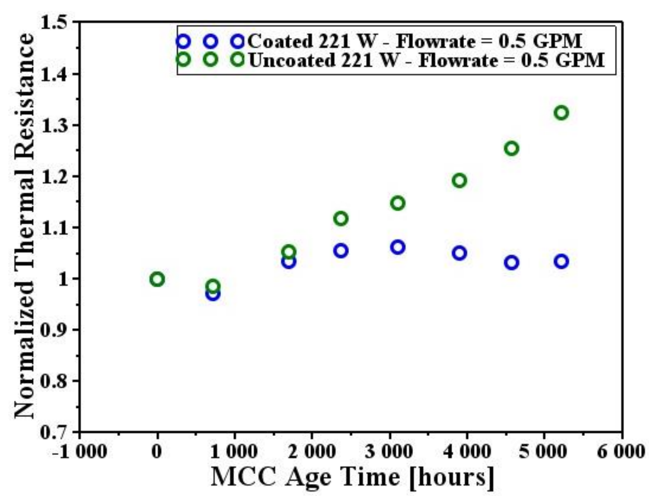

Fig. 14 Evolution of normalized MCC stack thermal resistance over test duration at a flow rate of 0.5 GPM

Uncertainty Analysis

To evaluate the significance of the calculated change in thermal resistance over the course of the copper MCC life test, and to obtain values for the error bars in the figures above, an uncertainty propagation analysis was performed. The total thermal resistance of each MCC stack is calculated from Eq. 1, which is a function of the four resistive heater temperatures, and the inlet and outlet temperatures of the DIW. Each of these temperature measurements has an associated uncertainty which carries over into the calculation of the thermal resistance. Additionally, temperature dependent DIW properties may introduce uncertainty to the measurement. The partial derivative with regards to each variable, and the uncertainty u of each variable is used to calculate the uncertainty of the thermal resistance calculation using Eq. 2.

$$u_{Rth} = \left\{ \begin{array}{c} \sum_{i=1}^{4} \left(\frac{\partial R_{th}}{\partial T_i} u_{T_i}\right)^2 + \left(\frac{\partial R_{th}}{\partial T_{in}} u_{T_{in}}\right)^2 + \\ \left(\frac{\partial R_{th}}{\partial T_{out}} u_{T_{out}}\right)^2 + \left(\frac{\partial R_{th}}{\partial \dot{m}} u_{\dot{m}}\right)^2 + \left(\frac{\partial R_{th}}{\partial c_p} u_{c_p}\right)^2 \end{array} \right\}^{1/2} \qquad \text{Eq. 2}$$

The uncertainty of the temperature measurements are obtained from the data using a 95% confidence interval of the mean. The specific heat is assumed to have a value of 4,184.5 J/kg·K and an uncertainty of 4.5 J/kg·K, which was determined based on the temperature dependence of the specific heat and the temperature rise of the coolant during experimental evaluations. The uncertainty in the mass flow rate is determined from the uncertainty in the volumetric flow rate ($\dot{V}$) that was recorded from a rotameter, which is assumed to be 10%, and the uncertainty of the fluid density, which is assumed to be 997.35 kg/m^3 ± 1.75 kg/m^3, again determined based on the temperature dependence of the density. Eq. 3 was used to calculate the uncertainty in the mass flow rate.

$$u_{\dot{m}} = \left\{(\rho u_{\dot{V}})^2 + \left(\dot{V} u_\rho\right)^2\right\}^{1/2} \qquad \text{Eq. 3}$$

The uncertainty of the MCC stack total thermal resistance calculation was found to be around ±10-12% and is represented by the error bars in Figures 8 – 11. The minimum uncertainty for the thermal resistance of the coated MCC stack was found to be 10.0% at both flow rates. The maximum uncertainty for the thermal resistance of the coated stack was found to be 11.0% at 0.3 GPM and 12.0% at 0.5 GPM. Similarly, the minimum uncertainty in the thermal resistance of the baseline uncoated stack was 10% at both flow rates, while the maximum uncertainty was 11.2% at 0.3 GPM and 12.4% at 0.5 GPM. Referring to Fig. 13 and Fig. 14, it can be seen that the thermal resistance of the baseline uncoated MCC stack increases over the course of the life test by 30-35%, which is a statistically significant increase. However, the thermal resistance of the coated stack varies by less than 10%, which is within measurement uncertainty.

PERFORMANCE DEGRADATION DUE TO EROSION-CORROSION IN MCCS

The total thermal resistance of the copper MCC stacks is a combination of conduction resistance through the MCC wall and internal fin structure and convective thermal resistance from the copper features to the DIW coolant stream. Thus, removal of material from the heat transfer surfaces due to erosion-corrosion may have an effect on both the conduction and convection components of the overall MCC thermal resistance. The increase in hydraulic diameter due to removal of material causes a reduction in convective thermal resistance, but also causes a corresponding reduction in the conduction thermal resistance through the copper wall and fin structure, which can cause competing changes to the total thermal resistance. However, a quick analysis shows that the conduction thermal resistance is an order of magnitude smaller than that of the convective thermal resistance, due to the small conduction length and high conductivity of copper. Therefore, any change in the material dimension from erosion-corrosion damage causes a negligible change in the conduction thermal resistance compared to the dominant convective thermal resistance.

The measured increase in thermal resistance and decrease in pressure loss of the baseline uncoated MCC stack was concluded to be due to an increase in the hydraulic diameter of the internal microchannels from erosion-corrosion. A theoretical evaluation was performed to support this conclusion. The influence of erosion-corrosion on the thermal resistance of theoretical square copper microchannels was examined, for a range of initial hydraulic diameters (100, 250, 500, and 750 µm) and constant erosion-corrosion rates (0.025, 0.05, 0.075, and 0.1 mm/yr) over a 10,000 hour exposure time. The Nusselt number correlation for microchannels proposed by Yu et.al. [8], assuming fully developed flow and a 0.1 GPM per channel flow rate of DIW with an inlet temperature of 25°C, was used to calculate a convective heat transfer coefficient in the channel. The total thermal resistance, including the thermal resistance of the base and the fin efficiency (assuming an initial thickness of 500 µm for both the base and fins), was calculated. Fig. 15 illustrates the dimensions used in the calculation, and the change in hydraulic diameter D_h due to erosion-corrosion.

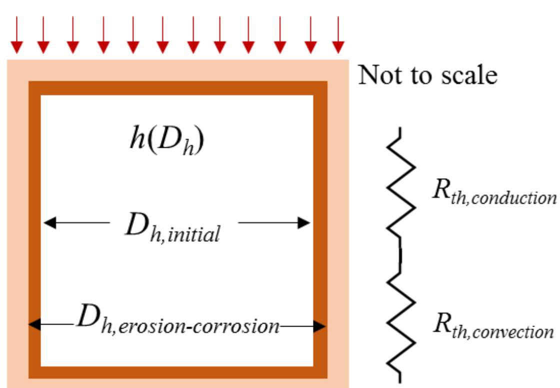

Fig. 15 Illustration of geometry evaluated in performance degradation prediction calculations

An area of 0.6 cm^2, which corresponds to the total footprint per stack of the resistive heaters in the test apparatus, was used to find the thermal resistance in units of K/W. The results for 100 and 250 μm channels are presented in Fig. 16. The results for 500 and 750 μm channels are shown in Fig. 17. As expected, the increase in hydraulic diameter causes a measurable increase in the overall thermal resistance of the microchannel cooler, driven by the reduction in convective heat transfer. Due to the complex geometry of the coolant flow passages in the copper MCCs used in the life test, a direct comparison between the experimental and theoretical results is not feasible. However, in general the hydraulic diameter of the internal features of the MCCs are in the 100-300 μm range. The measured MCC stack thermal resistances are reasonably close to those calculated above, in the range of 0.02-0.06 K/W. This qualitative comparison supports the conclusion that the measured increase in thermal resistance of the baseline uncoated MCC stack is due to the erosion-corrosion of the internal microscale heat transfer features. Conversely, the lack of change in the thermal resistance of the coated MCC stack suggests the suppression of erosion-corrosion effects.

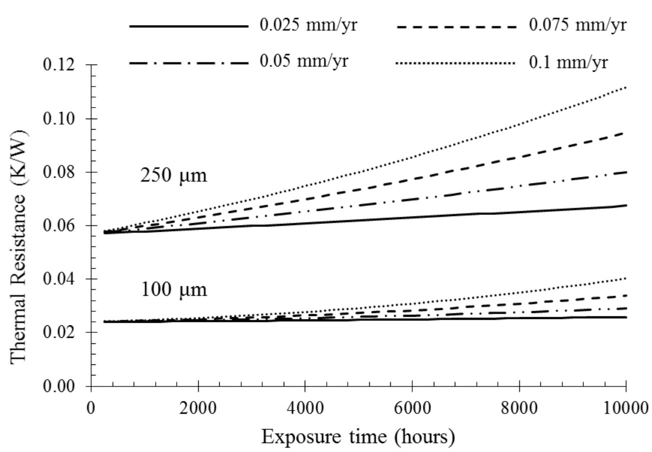

Fig. 16 Change in thermal resistance of a theoretical copper MCC with 100 μm and 250 μm channels, at different constant erosion-corrosion rates

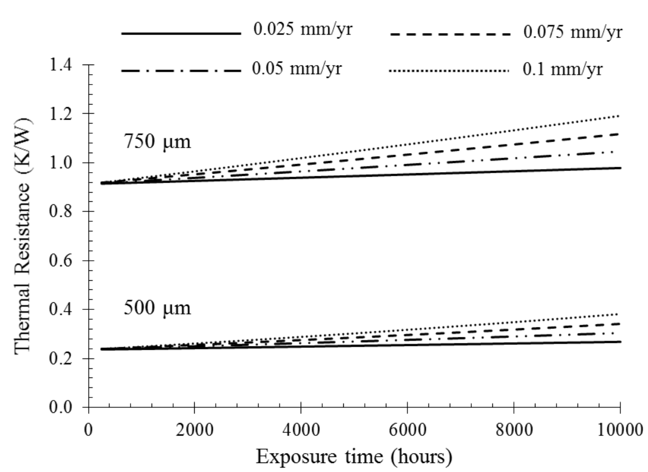

Fig. 17 Change in thermal resistance of a theoretical copper MCC with 500 μm and 750 μm channels, at different constant erosion-corrosion rates

CONCLUSIONS

High powered laser diodes are becoming increasingly more prevalent in many fields, such as military, material processing, and medical applications. These laser diodes require thermal management to dissipate the large amounts of waste heat that is produced by their operation. The typical thermal management strategy for laser diodes is to bond the diodes to the surface of a copper MCC, which uses high flow rate single-phase cooling, and also serves as the electrodes for energizing the laser. To reduce leakage currents to the coolant, high purity DIW is used. The combination of high velocities and the use of DIW produces a highly erosive and corrosive environment, which causes damage to the internal features of the MCC and a reduction in thermal performance, shortening the service life of the laser diodes. In order to extend the service life of the MCCs and laser diodes, a vapor phase deposition technique was developed to apply a hard, inert, nanometer thin coating to provide protection from these erosion-corrosion mechanisms. To evaluate the long-term performance of the coating to provide erosion-corrosion protection, an extended life test was performed. Two stacks of four MCCs each were subjected to the conditions of laser diode thermal management for over 5200 hours of continuous operation. One stack was assembled from four coated MCCs coolers, while the second was assembled from four baseline uncoated coolers. The thermal and hydraulic performance was monitored over the course of the life test. It was shown that the total thermal resistance of the baseline uncoated MCCs increased by over 30% over the course of the test, indicating the occurrence of erosion-corrosion damage. However, the thermal resistance of the coated MCCs did not vary significantly, indicating that the coating provides a protective barrier that suppresses erosion-corrosion in the MCCs. A theoretical analysis which calculated the change in thermal resistance in microchannels due to a change in hydraulic diameter from material removal supports the conclusion that erosion-corrosion in the MCCs causes an increase in thermal resistance. The results of this study demonstrate the ability of the applied nanoscale coating to provide erosion-corrosion protection and extend the service life of laser diode thermal management systems.

ACKNOWLEDGEMENTS

The authors would like to thank the Defense Advanced Research Projects Agency (DARPA) for supporting the development of this technology under contract number D11PC20206. The authors would also like to acknowledge Dr. Avram Bar-Cohen and Dr. Kaiser Matin for their guidance and input, and to acknowledge Curamik – Rogers Corporation for supplying the MCCs.

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