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# INVESTIGATION OF TITANIUM BONDED GRAPHITE FOAM COMPOSITES FOR MICRO ELECTRONIC MECHANICAL SYSTEMS (MEMS) APPLICATIONS


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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Materials Science and Technology Division
Advanced Manufacturing Office

# INVESTIGATION OF TITANIUM BONDED GRAPHITE FOAM COMPOSITES FOR MICRO ELECTRONIC MECHANICAL SYSTEMS (MEMS) APPLICATIONS

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## ACKNOWLEDGEMENTS

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## ABSTRACT

PiMEMS Inc. (Santa Barbara, CA) in collaboration with ORNL investigated the use of Titanium Bonded Graphite Foam Composites (TBGC) for thermal mitigation in Micro Electronic Mechanical Systems (MEMS) applications. Also considered were potentially new additive manufacturing routes to producing novel high surface area micro features and diverse shaped heat transfer components for numerous lightweight MEMs applications.

# 1. INVESTIGATION OF TITANIUM BONDED GRAPHITE FOAM COMPOSITES FOR MICRO ELECTRONIC MECHANICAL SYSTEMS (MEMS) APPLICATIONS

This phase I technical collaboration project (MDF-TC-2015-074) was begun on April 30, 2015, and was completed on December 31 2015. The collaboration partner PiMEMS Inc. is a small business.

## 1.1 BACKGROUND

PiMEMS is a small privately held company that designs, fabricates, and packages Micro-electronic-mechanical system (MEMS) devices using titanium.

PiMEMS Inc. in collaboration with ORNL investigated the use of Titanium Bonded Graphite Foam Composites (TBGC, ORNL IP, US Patent # 09017598) for thermal mitigation in Micro Electronic Mechanical Systems (MEMS) applications. The collaboration also investigated the potential for new additive manufacturing routes for producing high surface area micro-features on titanium substrates to improve wicking in MEMs applications.

PiMEMS Inc. has a commitment to the use of titanium for MEMs devices even though titanium has poor thermal properties. This effort combined titanium (as a binder matrix material) with high thermal conductivity (ORNL developed) graphite foam powder to yield high thermal conductivity composites to be integrated within a MEMs device. The target goal for Phase I was to reach or exceed 100 W/mK (for the XY “in-plane” orientation) for the ORNL proposed composites.

## 1.2 TECHNICAL RESULTS

ORNL prepared specimens of titanium bonded graphite foam powder consolidated by vacuum hot-pressing and measured the resulting thermal conductivity for the three proposed compositions. The compositions studied are outlined in Table 1. Flash diffusivity was conducted (by ORNL) on coin shaped samples 13 mm dia. x 4 mm thick. (Fig. 1.) Rule of mixtures (ROM) calculations were used to determine the specific heat for the different composites. Adjustments for the relative sample densities were also figured into the calculations. The samples were machined from vertical slabs- 4 mm thick (in order to determine the XY “in-plane” performance for the three compositions).

Rectangular samples were prepared at 40 mm x 50 mm x 1mm thick as requested by PiMEMs. Additionally, three small (10-40 mm x 1mm thick) samples were shipped to PiMEMS for evaluation and testing. (Fig. 1.)

Immersion density (Archimedes' method) was used to determine the densities of the hot-pressed samples and for comparison to their theoretical densities. As seen in Table 2, as the graphite foam content increased, the percent of theoretical density fell. Of particular interest is a corresponding reduction in the slope of the curve for improvement in thermal conductivity with increasing graphite content (Fig. 2.), with a maximum thermal conductivity of > 173 (W/mK) being measured at room temperature for TCP-3 (in air) in the XY in-plane direction.

Thermal diffusivity ($\alpha$) was measured with the Xenon flash facility located within the Thermal Physical Properties User Center at ORNL (High Temperature Materials Laboratory, HTML). The thermal conductivity ($\alpha$) was calculated using the relationship: $\kappa = \alpha\rho C_p$. A constant value for Cp of 1020 J/kgK for Koppers Inc. (P-1) foam and a value for Cp of 523 J/kgK for titanium metal was used for the calculation. Further processing optimization would likely improve the final composite density for the higher graphite containing composites and achieve further improvements in the final thermal conductivities.

| | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | PRESSED | | | | | | | | | | |
| 2 | PM-TCP-1 batch | 55% | | | | | | | | | |
| 3 | Sample | Component | ~ Relative | Weight | Density | Volume | T.D. | | | HOT PRESSED DISCS | |
| 4 | | | Volume | (g) | (g/cm^3) | (ml) | 3.27 | Vol % | Wt % | | |
| 5 | | | | | | | | | | 131.5 g = .5" x 2.5" ingot (40cc) | |
| 6 | PM-TCP-1 batch | Ti CP ITP ARMSTRONG | 44.90% | 130 | 4.506 | 28.85 | | 45% | 61.90% | 32.8.75 g = .125" x 2.5" ingot 10cc) | |
| 7 | | Coarse Ground P-1 Koppers | 55.10% | 80 | 2.26 | 35.40 | | 55% | 38.10% | 32.8.75 g = .125" x 2.5" ingot 10cc) TI FOIL | |
| 8 | | -140, +200 mesh | | 210 | | 64.25 | | | | | |
| 9 | | | | | | | Batch = >> | 64.25 | CC's | | |
| 10 | | | | | | | | | | | |
| 11 | PRESSED | | | | | | | | | | |
| 12 | PM-TCP-2 batch | 65% | | | | | | | | | |
| 13 | Sample | Component | ~ Relative | Weight | Density | Volume | T.D. | | | | |
| 14 | | | Volume | (g) | (g/cm^3) | (ml) | 3.05 | Vol % | Wt % | | |
| 15 | | | | | | | | | | 122.7 g = .5" x 2.5" ingot (40cc) | |
| 16 | PM-TCP-2 batch | Ti CP ITP ARMSTRONG | 34.95% | 105 | 4.506 | 23.30 | | 35% | 51.72% | 32.8.75 g = .125" x 2.5" ingot 10cc) | |
| 17 | | Coarse Ground P-1 Koppers | 65.05% | 98 | 2.26 | 43.36 | | 65% | 48.28% | 32.8.75 g = .125" x 2.5" ingot 10cc) TI FOIL | |
| 18 | | -140, +200 mesh | | 203 | | 66.67 | | | | | |
| 19 | | | | | | | Batch = >> | 66.67 | CC's | | |
| 20 | | | | | | | | | | | |
| 21 | PRESSED | | | | | | | | | | |
| 22 | PM-TCP-3 batch | 75% | | | | | | | | | |
| 23 | Sample | Component | ~ Relative | Weight | Density | Volume | T.D. | | | | |
| 24 | | | Volume | (g) | (g/cm^3) | (ml) | 2.82 | Vol % | Wt % | | |
| 25 | | | | | | | | | | | |
| 26 | PM-TCP-3 batch | Ti CP ITP ARMSTRONG | 24.98% | 83 | 4.506 | 18.42 | | 25% | 39.90% | 113.42 g = .5" x 2.5" ingot (40cc) | |
| 27 | | Coarse Ground P-1 Koppers | 75.02% | 125 | 2.26 | 55.31 | | 75% | 60.10% | 32.8.75 g = .125" x 2.5" ingot 10cc) | |
| 28 | | -140, +200 mesh | | 208 | | 73.73 | | | | 32.8.75 g = .125" x 2.5" ingot 10cc) TI FOIL | |
| 29 | | | | | | | Batch = >> | 73.73 | CC's | | |
| 30 | | | | | | | | | | | |
| 31 | PRESSED | | | | | | | | | | |
| 32 | PM-TCP-5-1small inv | 85% | | | | | | | | | |
| 33 | Sample | Component | ~ Relative | Weight | Density | Volume | T.D. | | | | |
| 34 | | | Volume | (g) | (g/cm^3) | (ml) | 2.60 | Vol % | Wt % | | |
| 35 | | | | | | | | | | | |
| 36 | | Ti CP ITP ARMSTRONG | 15.20% | 42 | 4.506 | 9.32 | | 15% | 26.33% | 113.42 g = .5" x 2.5" ingot (40cc) | |
| 37 | | Coarse Ground P-1 Koppers | 84.80% | 117.5 | 2.26 | 51.99 | | 85% | 73.67% | 32.8.75 g = .125" x 2.5" ingot 10cc) | |
| 38 | | -140, +200 mesh | | 159.5 | | 61.31 | | | | 32.8.75 g = .125" x 2.5" ingot 10cc) TI FOIL | |
| 39 | | | | | | | Batch = >> | 61.31 | CC's | | |

**Table 1 Sample Compositions**

| Sample | Vol. % Foam | Vol. % Ti | [W/mK] | Density | % TD |
|---|---|---|---|---|---|
| TCP-1 | 55.00% | 45.00% | 147.75 | 3.22 | 98.56% |
| TCP-2 | 65.00% | 35.00% | 172.29 | 2.94 | 96.30% |
| TCP-3 | 75.00% | 25.00% | 173.45 | 2.60 | 92.25% |
| TCP-4 | 85.00% | 15.00% | 156.27 | NA | NA |

**Table 2 Thermal conductivity and immersion densities of composite samples**

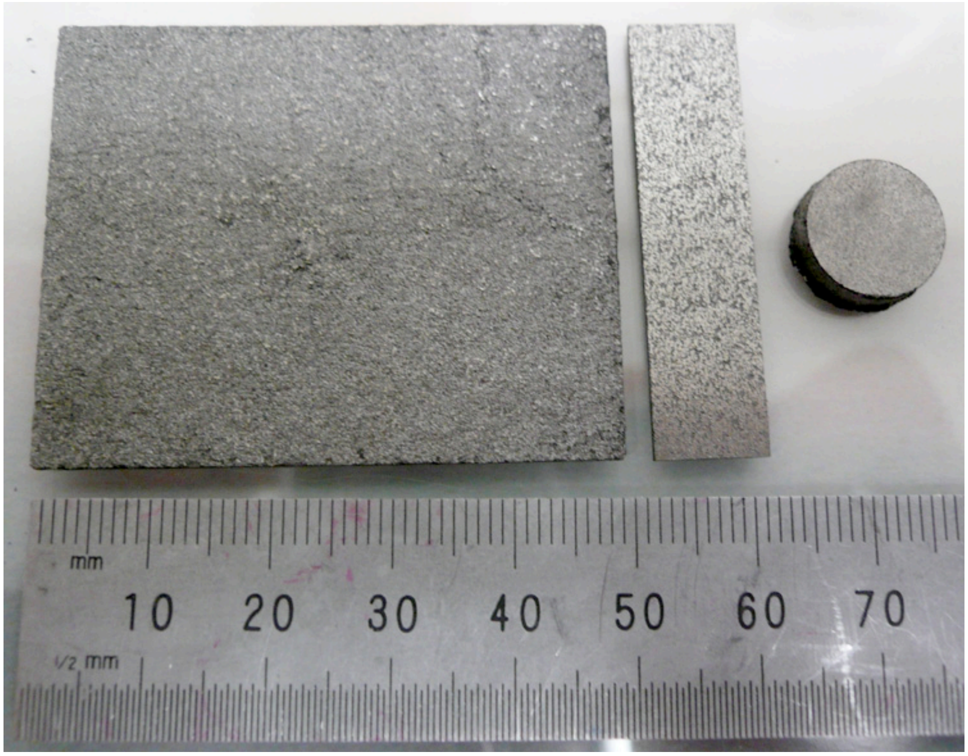


**Fig. 1. Test specimens for MEMs devices along with round flash diffusivity sample shown.**

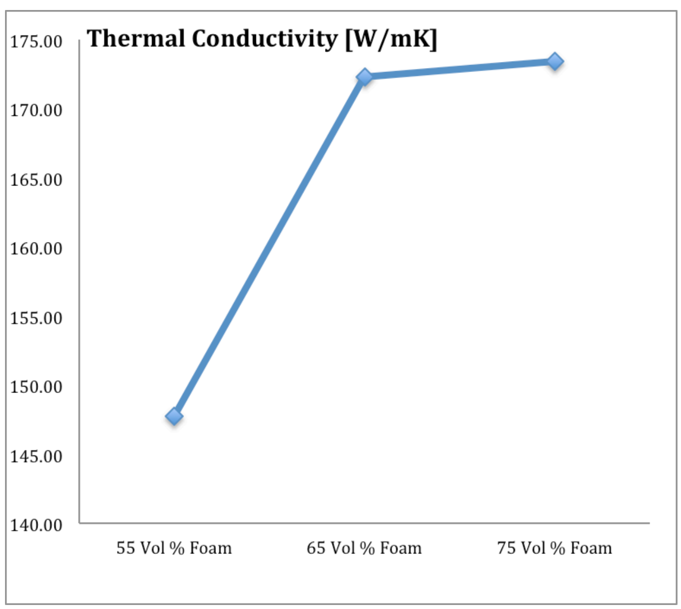


**Fig. 2. Thermal Conductivity (calculated) from Laser Flash Diffusivity measurements (ORNL).**

ORNL also investigated additive manufacturing (laser additive manufacturing on a Renishaw laser melting system) to produce high surface area features (micro-channels) on select specimens, which were faced with commercially pure (CP) titanium. These specimens were also evaluated by PiMEMs. Unfortunately, the print resolution and resulting surface features were too large to offer improved wicking for their MEMs devices. (Figs. 3- 6.) Profiles of printed lines show ~160 µm line thickness, which exceeds the 10 µm desired target thickness.

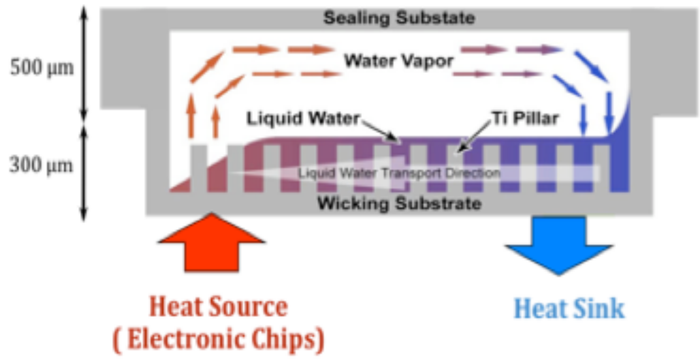


**Fig. 3. MEMS device concept.**

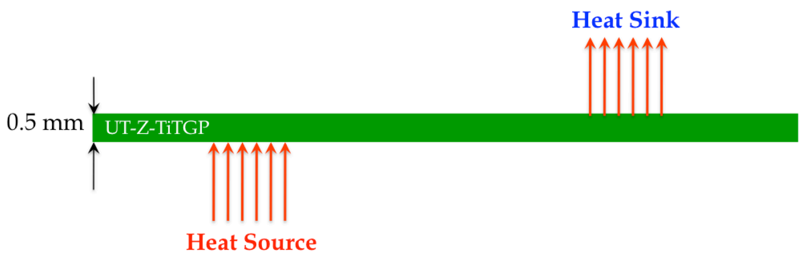


**Fig. 4. Thermal ground plane in use.**

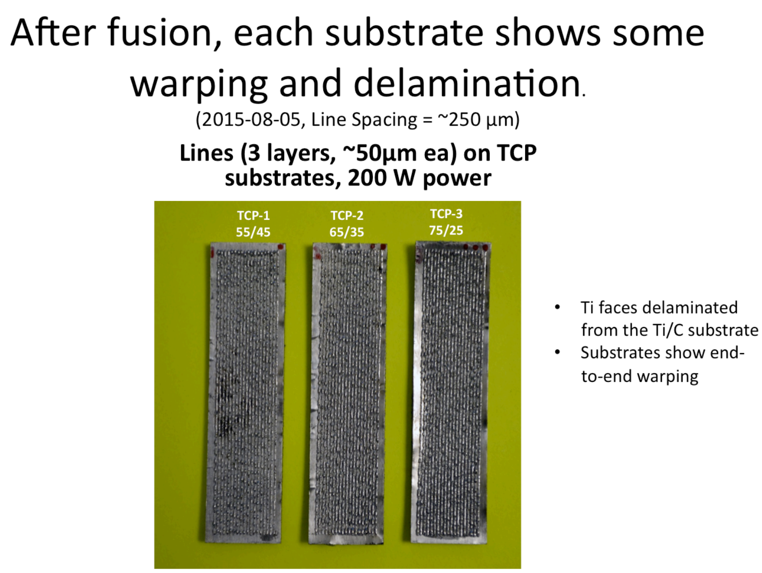


**Fig. 5. ORNL Titanium/graphite composites with AM micro-channels.**

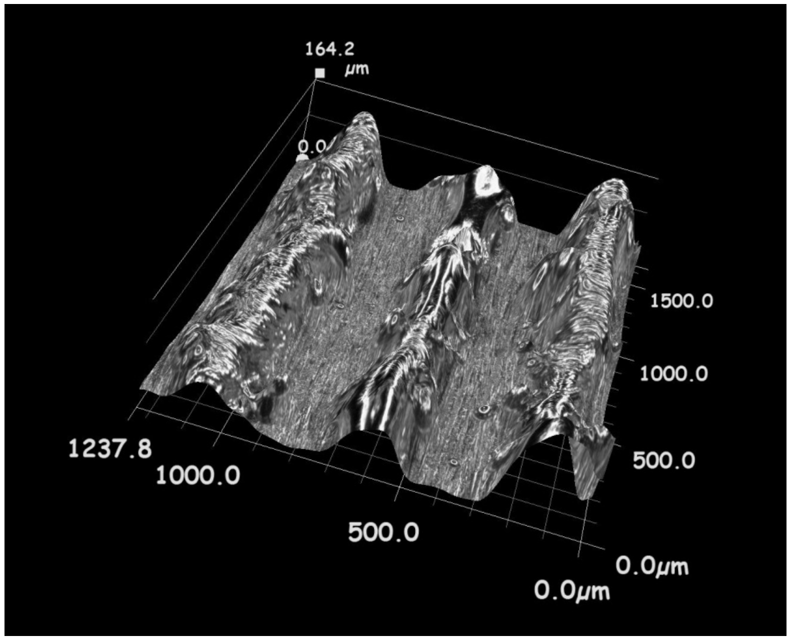


**Fig. 6. Profile shows ~160 µm line thickness (desired 10 µm)**

Thermal conductivity performance was also evaluated by PiMEMS using their in-house technique that measured the "lateral thermal conductivity" of the hot-pressed samples. The ORNL Ti-Graphite composites demonstrated an increase in the overall *lateral* thermal conductivity of the samples tested by a factor of 4 compared to the control sample (CP titanium).

## 1.3 IMPACTS

The potential for integrating the proposed technology in MEMs devices has been demonstrated although further improvements are recommended by PiMEMs.

The aspect ratio (width/depth) of the fabricated micro channels and mesh made by laser additive manufacturing on titanium substrates remain too large for micro fluidic and MEMS devices. If smaller channels with smaller surface roughness features (desired <10 µm features) could be demonstrated by further processing improvements, it might then be possible to utilize and integrate the proposed techniques for the manufacture of MEMs devices.

## 1.4 CONCLUSIONS

1- The applied TBGC method shows a potential to make a Ti-Graphite composite that increases the overall *lateral* thermal conductivity of the sample made by factor of 4 compared to CP titanium. However, the current approach needs to fabricate even thinner Ti-Graphite composites (100~300 µm) in order to be applicable for MEMS applications/devices.

2- The aspect ratio (width/depth) of the fabricated micro channels and mesh using laser additive manufacturing on titanium substrates is too large for micro fluidic and MEMS devices. Further processing improvements would be required in order to fabricate smaller features, channels and meshes.

## 2. PARTNER BACKGROUND

PiMEMS is a small privately held company that designs, fabricates, and packages Micro-electronic-mechanical system (MEMS) devices using titanium.

PiMEMS Inc. in collaboration with ORNL investigated the use of Titanium Bonded Graphite Foam Composites (TBGC) for thermal mitigation in Micro Electronic Mechanical Systems (MEMS) applications. (ORNL IP, US Patent # 09017598) The collaboration also investigated the potential for new additive manufacturing routes for producing high surface area micro-features on titanium substrates to improve wicking in MEMs applications.