Thermal and Aerodynamic Effects of Surface Roughness Patterns on Additive Manufactured Heat Sinks

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Abstract

Breakthroughs in heat sink design are now limited by conventional manufacturing techniques which can only produce basic fin shapes with homogenous surface structuring. Additive Manufacturing (AM) is a potential disruptive technology for heat sink design, particularly in high speed flows, as properties can be functionally graded to maximize performance for a prescribed environment and flow structure. This study examines the effect of surface roughness variation in the direction of 2-dimensional boundary layer development on plane fin heat sinks. Pyramid structures have been selectively applied to the surface of the sink to produce uniform $Ra'$s of 5, 15, 30, 43 and 71 microns on heat sinks that were created to have a roughness gradient in a directions parallel and perpendicular to ambient flow. In anticipation of aerospace environments, the experimental facility trips the boundary layer to turbulence and is placed in the centerline of the wind tunnel in order to expose the sink to the maximum possible velocity. A plane flat surface and heat sink with a uniform surface roughness of 5 microns, validated by an optical white light interferometer matched theoretical expectations for turbulent conditions. The turbulent condition is required in order to fully exploit roughness gradients as laminar flow is surface finish agnostic. A thermal conductivity of 11.9 W/m-K was found using a Thermal Interface Material (TIM) tester, showing a significant reduction in this property relative to the expected property of bulk aluminum which has been conventionally machined. This reduction is due primarily to the porosity of the internal structuring which is an artifact of the Selective Laser Melting (SLM) process used to fabricate the heat sinks. Using a 7 plane fin heat sink where each 0.1” thick fin is spaced 0.13” apart, a minimum thermal resistance of 0.23 K/W was found. Graded roughness in the direction of the flow was found to have no effect on thermal resistance, however, gradients in the direction normal to the bulk flow were found to decrease the thermal resistance by 3.5% for a Reynolds number range of 8300 to 28700 where the Reynolds number is based on the characteristic length of double the spacing between the fins. Improvements in thermal resistance reached as high as 15.2% when comparing heat sink with full maximum surface roughness patterns distributed evenly across the fins, coming at a weight increase of 4-12%. Intelligent heat sink design which exploits the surrounding flow conditions can improve performance drastically with minimal increase to heat sink weight and volume. However, this functionally graded roughness parameter is only possible through AM techniques. Positive impacts on performance from roughness gradients introduces the possibility of even more spatially resolved gradients which are tuned using numerical modelling of the surrounding flow structure and hydrodynamic boundary layer development.

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