Development of Copper MIM Powders for Thermal Management Applications

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Abstract

Metal Injection Moulding is continuing to see strong growth in the variety and volume of parts and materials in use. We report here the development and application of fine copper powders for MIM of heat sinks for thermal management applications. This is an important field for development in view of the increasing need for cooling of compact electronic devices and the need to use cost effective net-shape forming methods for expensive materials. Sandvik Osprey Ltd. has produced fine, low oxygen powders (90% -22µm and 90% -31µm) which have been incorporated into MIM feedstock at ARC Seibersdorf. The properties of the finished components are presented and the potential for applications in thermal management is discussed.

INTRODUCTION

Copper is a particularly suitable material for thermal management applications due to its high thermal conductivity and relatively high sintering activity. In combination with a net-shape process like MIM, complex heat sink components with optimized thermal features can be manufactured [1,2]. Composite structures integrating porous elements for heat pipes are also in development.

Johnson & Lye-King Tan [2] have reported development of copper MIM parts using a variety of copper powder feedstocks made by different processes. This study highlighted the importance of porosity and impurities in affecting the conductivity of finished parts. Sintered densities in the range 93-96% and thermal conductivities in the range 280-385 W/mK were reported. At the high end, these values approach the performance of wrought copper but with the advantage of cost effective manufacturing.

One of a number of heat sink components under development is shown in Figure 1. The part is a heat sink for an automotive thermal management application where a power LED is mounted on a PCB on the flat surface. The energy which is not converted into light (about 80%) is removed from the LED via this array of thin-walled cylindrical structures [3]. In this paper we report the manufacture of this part by MIM and the evaluation of its thermal performance against design targets.

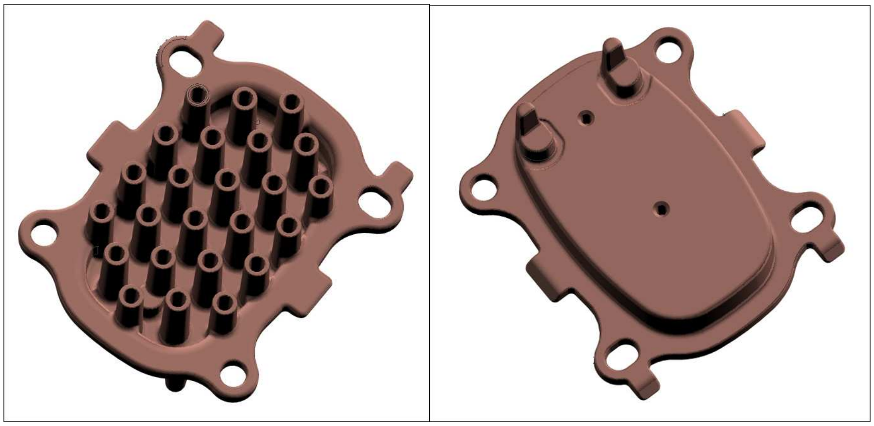


Figure 1. LED heat sink for thermal management

EXPERIMENTS

The copper powders used for this study were supplied by Sandvik Osprey Ltd. They were produced from the same lot of HC (High Conductivity) copper which was gas atomised in nitrogen and air classified to produce separate fine fractions at 90%<31 microns and 90% <22 microns. The atomising conditions were designed to minimise oxygen pick up and product was stored in vacuum packaging before use. The oxygen level for each powder was measured at 0.055% and 0.078% respectively.

Table 1 shows the particle size distribution characteristics d10, d50 and d90 of the powder feedstocks measured using a Malvern Mastersizer.

Table 1. Particle size distribution and powder density of starting materials.

Product	***D10 µm***	***D50 µm***	***D90 µm***
90% <31 µm	*6.0*	*14.5*	*30.5*
90% <22 µm	*4.9*	*10.6*	*21.8*

Feedstock Fabrication

The copper powders were compounded to feedstock using a proprietary wax-polymer binder system. An optimised powder loading of 60 vol % obtained from previous rheological characterization and torque evaluation proved suitable. The binder components were mixed with the metallic powder at room temperature in a Turbula Mixer to homogenize the batches of a Werner-Pfleiderer double-sigma compounder. The pycnometric density of fresh, treated powders and feedstocks was evaluated by a Quantachrome pycnometer.

Component Fabrication

Before the actual component fabrication started, three-point-bend bars and tensile test bars for both thermophysical and mechanical testing were produced using an Arburg 320 C injection moulding machine (Figure 2).

Figure 2. Injection moulding machine used for component fabrication at ARC Seibersdorf research GmbH

After these initial tests, the actual components were manufactured. The tooling used comprised a mould frame with 230 mm by 180 mm inserts (Figure 3).

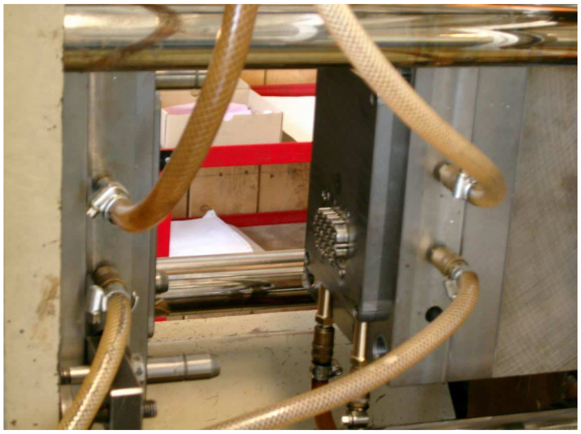


Figure 3. Mould frame with mould inserts

Injection moulded components are shown in Figure 4. Even though the component is relatively large (approx. 100 g), filling and demoulding of the component was quite straightforward.

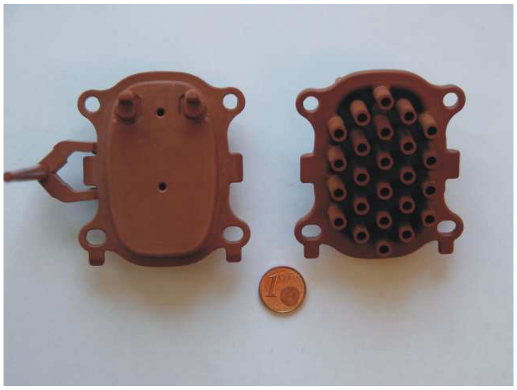


Figure 4. Injection moulded LED heat sinks

Combined debinding and sintering took place under hydrogen atmosphere and with a maximum temperature of 1030°C. The furnace which is equipped with a binder trap and a burn-off stack for efficiently removal of the binder components is shown in Figure 5.

Figure 5. Combined debinding and sintering furnace for maximum temperatures of 1100°C

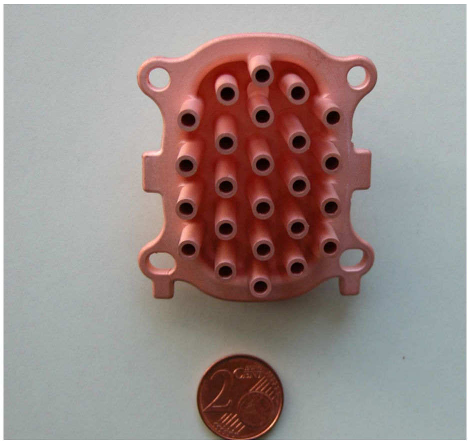


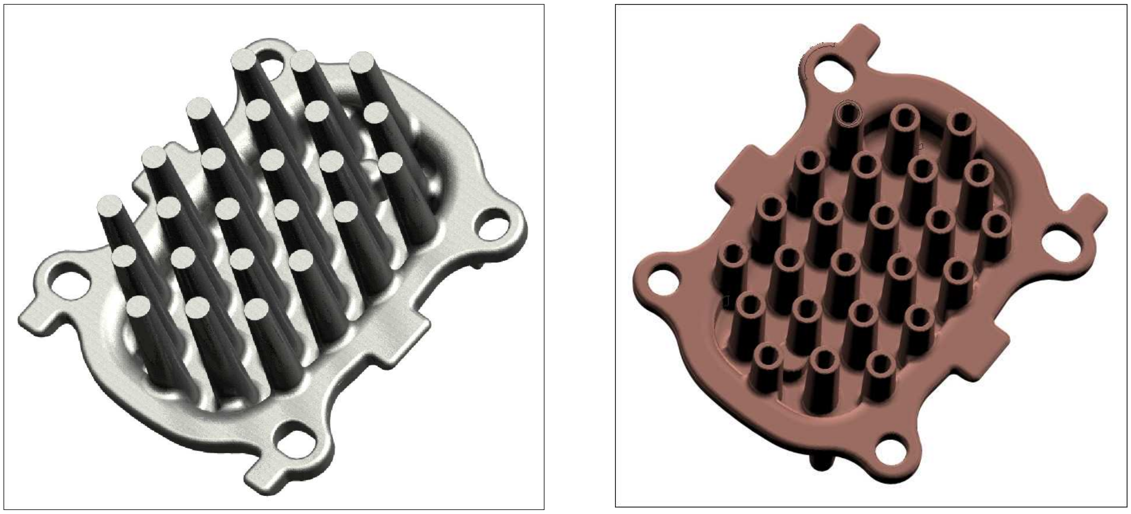
Figure 6. Sintered component: dimensions 56 mm x 48 mm x 32 mm (height)

RESULTS

Optimisation of Thermal Management Characteristics

The original solution for the heat sink was an aluminium high pressure die-cast component. Due to the limitations of this manufacturing process and the non-ideal material properties, the "thermal budget" was only just enough to remove the heat loss of one 1.25W power LED. In future, multiple power LEDs have to be mounted on the same available space: therefore an improved thermal management concept had to be developed. Using calculations based on the VDI Wärmeatlas [4] on free and forced convection, the geometry of the component has been optimized. By additionally using copper as a material with high thermal conductivity, it was possible to find a solution which can deal with the energy of four 1.25 W LEDs under the same special boundary conditions (Figure

7). It was assumed that a thermal conductivity of 380 W/mK could be achieved which had to be validated later in the thermophysical characterization.



Material: G-AlSi
Volume: 16,40cm³
Surface: 130,30cm²
Overall height: 27,50mm
Heat dissipation: 1,25W (1 LED)

Material: Copper
Volume: 11,80cm³
Surface: 140,50cm²
Overall height: 19,25mm
Heat dissipation: 5,00W (4 LEDs)

Figure 7. Old and new design for LED heat sink

Thermophysical Characterization

The main material property which has to be optimized for the LED heat sink application is the thermal conductivity. OHFC copper with a density of 8,93 g/cm^3 has a thermal conductivity in the order of 390-400 W/mK. Therefore one of the main challenges is to optimize the injection, the debinding and sintering process in order to have zero porosity in the sintered material.

In a first the step we were interested in the influence of different raw materials (Cu powders with size of <31 µm and <22 µm) on the thermal properties.

Therefore samples with a size of approx 80x10x6mm were prepared under identical conditions (the same injection parameters, debinding & sintering conditions as used for the LED heat sink) and tested with respect to the thermophysical properties. From these sintered parts, test samples for the different thermophysical measurements were cut out. Thermal diffusivity, specific heat and the Coefficient of Thermal Expansion (CTE) were measured as a function of temperature in the range of RT to 300°C. For the calculation of thermal conductivity, the following relationship was used:

$$\lambda(T) = a(T) \cdot \rho(T) \cdot c_P(T) \quad \text{or} \qquad (1)$$

$$\lambda(T) = a(T) \,.\, c_p(T) \,.\, \rho(T); \text{ where } \rho(T) = \rho_0 \,.\, (1 + \alpha \,.\, \Delta T)^3 \qquad (2)$$

$$\lambda(T)\text{..........}\textit{Thermal Conductivity [W/mK]}$$

$$a(T)\text{..........}\textit{Thermal Diffusivity } [m^2/s]$$

$$\rho(T)\text{..........}\textit{Density } [kg/m^3]$$

$$c_p(T)\text{..........}\textit{Specific Heat [J/kgK]}$$

$$\alpha(T)\text{...........}\textit{CTE}[K^{-1}]$$

In the case of materials with high thermal conductivity (>100 W/mK) the more precise technique for determining the thermal conductivity is via measurement of the thermal diffusivity. The thermal conductivity can be calculated using thermal diffusivity (measured by a laser flash system), specific heat (measured by Dynamic Scanning Calorimetry, DSC) and density (measured via Archimedes principle) data according to the relationship (1). For the measurement of the density as a function of temperature, CTE data (measured by dilatometer) can be used.

The used technique for measurement of thermal diffusivity is a laser flash method. This method is based on a laser, which fires a pulse at the sample's surface and the infrared detector measures the temperature rise of the surface. The laser has energy of some Joules and the duration of the pulse is about 0.5 ms. The induced heat pulse propagates in the sample and results in a temperature increase at the surface of the sample. The temperature increase as a function of time is directly proportional to the thermal diffusivity. The software uses literature-based analysis routines to match a theoretical curve to the experimental temperature rise curve. The thermal diffusivity value is associated with the selected theoretical curve.

The measurements for all thermal properties have been done at different temperatures. In the following section the results of sintered parts prepared from two different powders (D90 < 22 µm and D90 < 31 µm) are compared. The densification achieved for the sintered compacts was 96,5% for the 22 µm powder and 95,5% for the 31 µm powder.

The results of the thermophysical properties as a function of temperature are be shown in the following diagrams. For comparison the literature value of pure copper is shown.

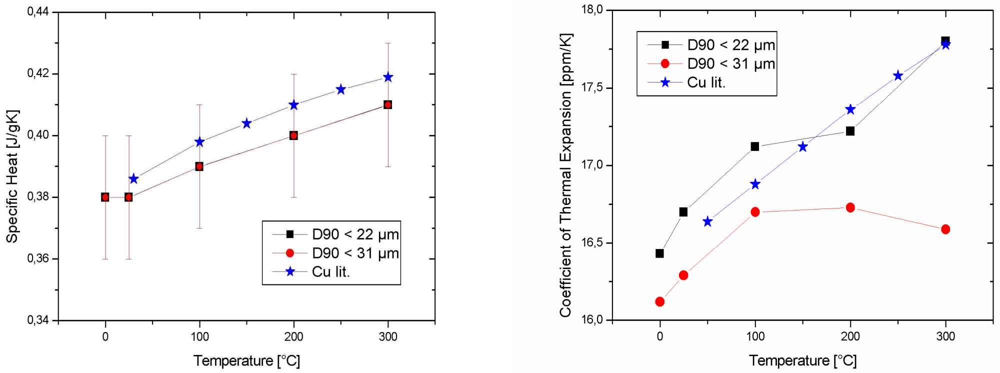


Figure 8. Specific heat and CTE as a function of temperature for sintered parts made of 22 µm and 31 µm copper powder compared to literature values of pure copper.

The specific heat for both materials shows more or less identical behavior as a function of temperature. For the CTE a different behavior at higher temperature is observed which might be due to a greater amount of porosity in the sintered sample for the Cu powder with 31 µm (Figure 8).

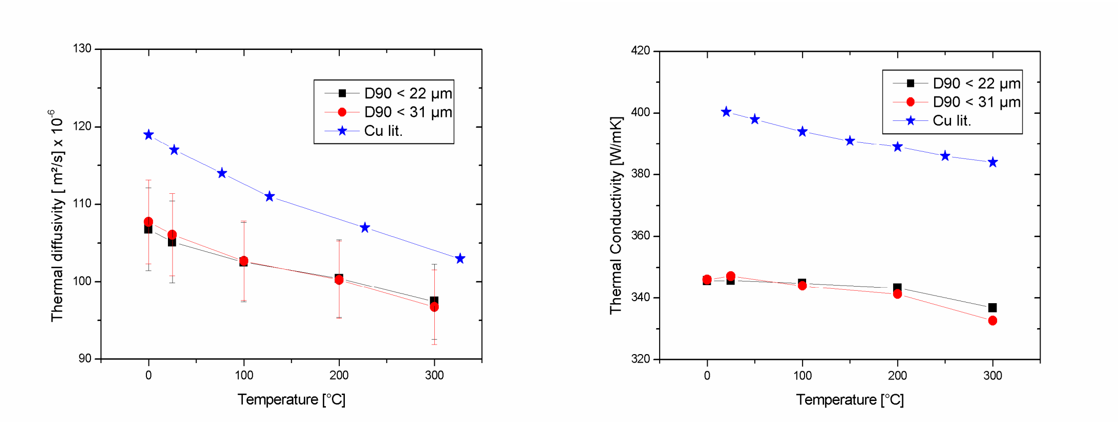


Figure 9. Thermal diffusivity and derived thermal conductivity of sintered parts made from 22 µm and 31 µm copper powder compared to literature values of pure copper.

For both powder materials a similar thermal behaviour is visible. Even due to a higher porosity in the Cu powder with a size of 31 µm the thermal diffusivity and conductivity (Figure 9) are more or less identical. Of course a 1% difference in porosity should result in a difference in the thermal diffusivity/conductivity but there maybe a secondary influence of particle size acting against the expected benefit of lower porosity. A smaller powder size may be related to a smaller grain size in the sintered compact which means that the amount of grain boundaries (and therefore additional thermal barriers) is higher than for the coarse powder.

DISCUSSION

This study has found that the two special copper materials tested are suitable for injection moulding of high-end thermal management components. In the particular application for a LED heat sink a four-fold increase in energy dissipation could be achieved as compared to a pressure die-cast solution in aluminium. Therefore, these materials offer huge potential for further applications in the future as thermal management becomes more and more of a bottleneck when it comes to increasing the power density of LEDs.

Both design variations with increased heat exchange surface and materials with optimum thermal properties will be necessary to fulfill the ever increasing thermal requirements. However, this comes at a cost. For the heat sink design shown in this study, the initial solution which is suitable for one LED mounted on it costs around 0.70 € each in numbers of larger than 100.000 per year. In comparison, for the optimized material and the fabrication using MIM it was calculated that the costs would be around 2.20 € each for the aforementioned volumes per year. Therefore, this solution is only justified when the power density of LEDs further increases. There are many indications that this is already the case and it is just a question of time before the current material-manufacturing combinations will reach their limits.

The thermal properties of the materials investigated (two different sizes of the starting powder) are quite similar although a further optimization of the material will be necessary to get a 100 % dense sintered compact. At the moment both materials reach more than 85% of the thermal conductivity of a pure copper standard. Therefore further optimization is necessary, e.g. using additional heat treatment etc. The reason why the Cu powder with a size of 22 µm did not show a better performance – despite a 1 % higher density – is expected to be due to a larger number of grain boundaries. These grain boundaries will act as additional barriers for the transfer of heat. To confirm this, a detailed analysis of the microstructure will be carried out.

Both raw materials are suitable for PIM and resulting in quite similar thermal properties. Depending on the application and the geometry of the component the appropriate powder can be chosen, e.g. the fine powder for complex shaped and thin walled components.

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