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SINTERED ALUMINUM HEAT PIPE (SAHP)

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ABSTRACT

This work is the product of an ongoing PhD project in the School of the Built and Natural Environment of Northumbria University in collaboration with the University of Liverpool and Thermacore Europe Ltd. The achievements at the end of the first year are summarized. The main objective of the project is to develop an aluminum ammonia heat pipe with a sintered wick structure. Currently available ammonia heat pipes mainly use extruded axially grooved aluminum tubes as a capillary wick. There have been a few attempts of employing porous steel or nickel wicks in steel tubes with ammonia as the working fluid (Bai, Lin et al. 2009) although it is a common practice in loop heat pipes but there is no report of aluminum-ammonia heat pipes porous aluminium wick structures. The main barrier is the difficulty of sintering aluminum powders to manufacture porous wicks. So far during this project promising sintered aluminum heat pipe samples have been manufactured using the Selective Laser Melting (SLM) technique with various wick characteristics. This SLM method has proven to be capable of manufacturing very complicated wick structures with different thickness, porosity, permeability and pore sizes in different regions of a heat pipe. In addition the entire heat pipe including the end cap, outer tube wall, wick and the fill tube can be generated in a single process.

KEY WORDS*:* Sintered Ammonia Heat pipe, SLM, heat transfer

1. INTRODUCTION

The first investigation of ammonia as a working fluid for heat pipes was done in late 60s and the first use of an ammonia heat pipe was in the early 1970s. They have been used in spacecraft as a mean for managing internal temperature conditions. To date, nearly all space radiator systems have used axially grooved aluminium/ammonia heat pipes or loop heat pipes (Anderson, Dussinger et al. 2008).

Axially grooved heat pipes offer relatively simple industrial fabrication and greater reliability than other wick designs, such as arterial heat pipes. Their principal function is to transport heat from dissipative equipment to radiative panels, creating an isothermal temperature profile temperature over the surface of the panel (Hoa 2003).

There is no record of an aluminium ammonia heat pipe with a porous wick structure in the literature.
The main reason for this seems to be in the fact that almost all the existing heat pipe porous wicks are made by the powder sintering method. While aluminium powder sintering is possible it is very difficult to fuse the powder due to the hard aluminium oxide layer on the surface of the powder particles. Current sintering methods use fluxes that are difficult / impossible to remove and are incompatible with ammonia resulting in non-condensable gas generation. Therefore they are not practical for manufacturing heat pipe wick structures. Also, manufacturing the porous wick from other materials and applying it on the internal walls of an aluminium heat pipe has many other complications including compatibility and wick-wall thermal resistance and assembly issues.

Developing an aluminium ammonia heat pipe with a porous wick structure is the main subject of this project and this paper reports the results of this project at the end of year one. For simplification, during the project this type of heat pipe is called SAHP or Sintered Aluminium Heat Pipe. However it is understood that this short name is subject to controversy as the porous structures which are discussed through this project are not developed by sintering method but with Selective laser Melting (SLM) technique.

As this is the first time that a heat pipe has been fabricated using this SLM technique, there are numerous questions that must be answered and of parameters which must be analysed or tested before the design rules for manufacturing heat pipes using this new method can be developed.
There are two groups of these parameters. First are the SLM machine settings in order to make acceptable solid structures (heat pipe container) and also porous structures (heat pipe wick). The second group are the characteristics of the heat pipe itself especially with regard to the porous wick structure e.g. the maximum heat removal, porosity, permeability and pore radii.

So far, during this project, solid and porous structures have been made by SLM to characterise their basic parameters. Then dummy heat pipes were manufactured to prove SLM capability in making different types of aluminium porous wick structures with the container, end cap and fill tube all in a single process.
Building operational heat pipe samples, filling and venting them and testing their thermal performance in various orientations is the ongoing activity and the results of this work will be presented in the future.

2. Manufacturing of the samples

2.1 Selective Laser Melting (SLM)

Selective Laser Sintering/Melting (SLS/SLM) is an additive layer manufacturing process that utilises a laser beam to locally melt a thin layer of metal powder. By applying additional powder layers and using 3D CAD and custom beam control software to melt a pattern across each layer, complex 3D components that are not able to be manufactured using conventional machining are produced (Almeida 2004).
The SLM process begins with a completely defined CAD model of the part to be made. Divided into cross-sections by special software, the model is then directly involved in the process. The essential operation is the laser beam scanning over the surface of a thin powder layer previously deposited on a substrate. The forming process goes along the scanning direction of the laser beam. Each cross-section (layer) of the part is sequentially filled with elongated lines (vectors) of molten powder (Yadroitsev, Bertrand et al. 2007).
Different aspects of the laser treated surfaces have been studied in literature e.g. corrosion (Liu, Chong et al. 2006), optimum value of the process parameters (Yadroitsev, Bertrand et al. 2007) and residual stresses (Mercelis and Kruth 2006).

The samples for this project were manufactured by MCP Realizer 100 (MTT Tooling Technologies, UK) SLM machine. A ytterbium fibre laser with maximum laser output of 200 W having continuous wavelength (CW), λ=1.071μm and nominal beam diameter of 50μm was employed in the machine. The optical system controls the movement of the focused laser beam on the build substrate having accuracy of +/- 5μm.
The processing chamber operated at a positive argon pressure of 14 mbar with oxygen levels kept between 0.1% - 0.2%. The atmosphere within the chamber is circulated and filtered to remove processed bi- products such as particles formed from condensed metal vapour, from the recycled gas. The specimens were manufactured layer by layer on an aluminium substrate plate secured on an elevator plate that moved vertically downwards allowing the controlled deposition of powder layers at 50μm intervals. The power and exposure time of the laser during each layer projected in spots is set from a defined process window. These parameters control the degree of melting at each laser contact spot and the melt pool, which in turn controls the strut diameter of the porous structures and consequently their porosity and strength. Porous structures are generated by formation of octahedral units, repeated in a constrained boundary representing structural geometry. The build substrate plate is removed from the build chamber after completion of build and un-fused powder is removed by applying a vibratory action to the up-turned plate. Test pieces are then cut from the substrate plates using a wire erosion process to avoid excessive smearing of the pores. Figure 1 shows a substrate with some random geometry fabricated on it;

Figure 1: In SLM machine, objects are made on a substrate and then are cut using a wire erosion process. A substrate is shown here with some random geometry fabricated on it.

To prepare a CAD model for the SLM machine first the entire geometry is enclosed in a bounding box. The box is then filled with cuboids of a defined unit cell size (in this project, 300, 500 and 700µm).

For those parts which meant to be porous these cuboids are populated with a 3-D octahedral geometry. Then the entire geometry is sliced into layers with specific thickness (in this project, 50µm). Specific commands are applied to change the Cartesian coordinates of the octahedral structure's centre point if randomising of the structures is required (to obtain porous structures with a mix of pore radii's as opposed to homogeneous porous structure).

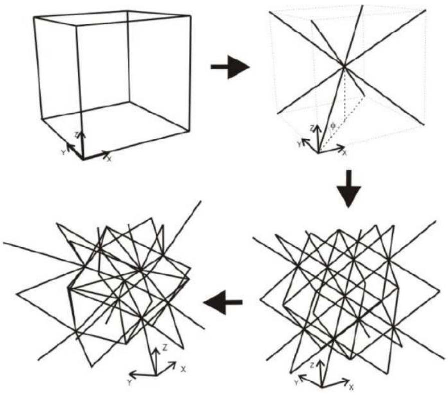

Figure 2: Transformation of the unit cell into a regular or randomised porous structure. [ref: Stamp, R. C., (2007)" The Rapid manufacturing Of Hierarchical Structures For Orthopedic Applications." PhD. University of Liverpool]

Figure 3: Randomised and regular (in inset) geometry structures

2.2 Manufacturing of the prototypes

SLM solid structures are defined by the laser point distance, hatch distance and exposure time of the laser beam. A series of thin walls were manufactured to understand the relation between these as shown in Figure 4;

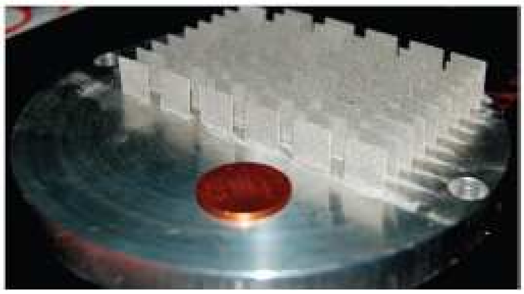

Figure 4: Al6061 thin walls made by SLM

Then a series of solid blocks were fabricated using a point distance of 0.01mm with various exposure times and hatch distances as shown below;

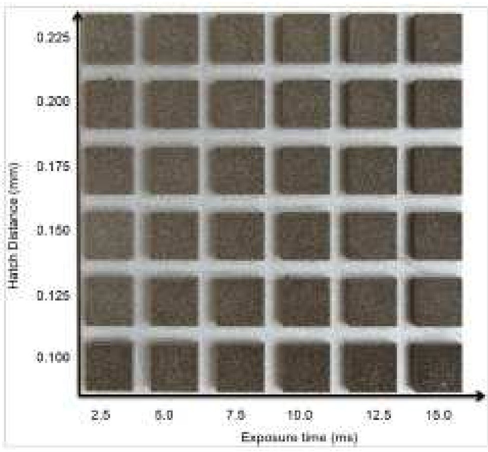

Figure 5: Al6061 solid blocks fabricated with different exposure times and hatch distances

SLM has previously been used for making porous structures e.g. porous finned heat sinks but only in the course of this project it has been used, for the first time, to make porous structures to work as a heat pipe capillary wick.

Initially, regular porous structures of 15x15x15 mm block of 300, 500 and 700µm octahedral unit cell sizes were manufactured. The porous structures with 500µm and 700µm unit cell porous structures were brittle, requiring higher energy for melting. This was achieved by manufacturing them at a higher exposure time. Figure 6 shows regular and 30% randomised porous structures manufactured from Al6061;

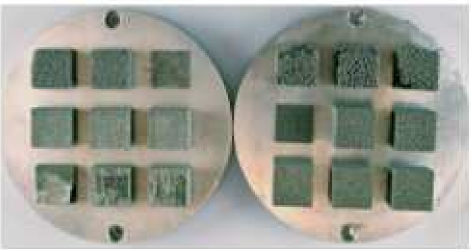

Figure 6: Al6061 regular (left) and 30% randomized (right) blocks fabricated with 300, 500 and 700µm unit cell sizes from bottom row to the top row respectively

A set of porous samples were also manufactured for permeability testing. These specimens were manufactured in Ø13 mm porous structures surrounded by thin solid wall of 0.2 mm, Figure 7. Therefore during permeability test, water will flow through top and bottom surfaces of the porous specimen, but there is no leakage along its length and through side walls.

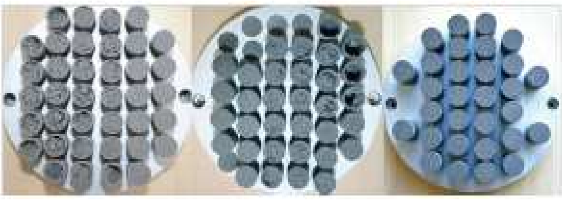

Figure 7: Porous samples made for permeability measurements. Different tries improved the quality as shown above from first build on the left to the 3rd build on the right

After analysing the solid and porous structures various designs were proposed for manufacturing heat pipes on SLM. In order to check the feasibility to manufacture the proposed designs, specifically axial grooved heat pipe (AGHP), a preliminary 20 mm section of heat pipe was built in titanium. Then the same geometry was made from Al6061 and 60mm length.

Al6061 was being used in SLM for the first time while there is a lot more knowledge about handling AlSi12 in SLM process so other samples were made using AlSi12. These samples were to prove the ability of SLM in manufacturing complicated wick structures. In total four different wicks structures were manufactured to demonstrate the ability of the SLM process to produce complex structures, suitable for heat pipes. The annular wick sample is shown in Figure 8.

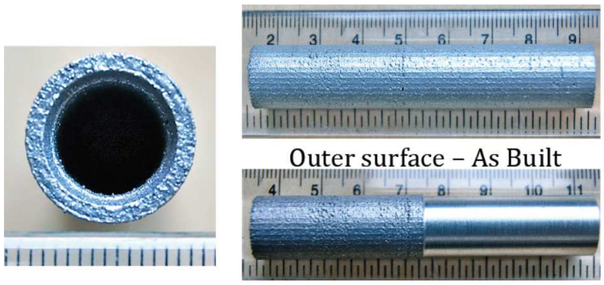

Figure 8: Annular wick heat pipe from AlSi12. Right top shows the outer surface of the pipe as built and right bottom after getting machined partially

One end of these heat pipes is already sealed and the whole heat pipe including the bottom cap, solid walls and porous wick is built in a single process. Additional features can also be integrated during the SLM process.

3. Analyzing the samples and prototypes

The density of the SLM solid structures was measured for different SLM machine setting. This density changes from 74.03% to 98.87% for different exposure times and hatch distances.

Considering the high vapour pressure of ammonia it is still not known if this density is enough for the pipe solid walls to provide required strength and leak freeness.

Heat pipe samples all passed the bubble leak test. The air inside the pipe was pressurised up to five bars under water and no bubble was observed. Samples were also tested for helium porosity. The pressure inside the tube was brought down to 10^{-7} Torr and helium then blown over the outer surface. Any helium that leaked into the pipe was detected by the instrument.

The overall permeability of all the porous samples was measured by a test rig specifically designed for these samples. The water flow rate through the sample was measured at a constant back pressure (constant water level above the sample) and assuming a unidirectional and steady flow Darcy's law (Equation 1 below) was used to calculate the bulk permeability;

$$V = \frac{Q}{A} = \frac{K}{\mu}\left(\frac{\Delta P}{l}\right) \qquad 1$$

Measured permeability for different samples is shown in table 1;

Sample	Description	Permeability	Sample	Description	permeability
1	500µm, Random	1.12×10^{-10}	11	300µm, Regular	2.22×10^{-13}
2	500µm, Random	1.47×10^{-10}	12	300µm, Regular	3.31×10^{-13}
3	500µm, Random	2.06×10^{-10}	13	300µm, Regular	3.23×10^{-13}
4	500µm, Random	1.93×10^{-10}	14	300µm, Regular	2.70×10^{-13}
5	500µm, Random	1.53×10^{-10}	15	300µm, Random	2.95×10^{-13}
6	500µm, Regular	2.74×10^{-10}	16	300µm, Random	3.80×10^{-13}
7	500µm, Regular	2.85×10^{-10}	17	300µm, Random	7.80×10^{-13}
8	500µm, Regular	2.86×10^{-10}	18	300µm, Random	4.70×10^{-13}
9	500µm, Regular	2.86×10^{-10}	19	300µm, Random	2.85×10^{-13}
10	500µm, Regular	2.52×10^{-10}	20	300µm, Random	1.65×10^{-13}

Table 1 Measured permeability for different SLM made porous structures

Permeability changes from 10^{-10} m^2 for 500µm unit cell samples to 10^{-13} m^2 for 300µm samples and no meaningful difference was observed between the random and regular porous structures.
SLM porous structures are believed to have negligible number of isolated pores due to the nature of the process thus almost-identical effective porosity and total porosity.

Porosity of the SLM porous samples was measured by imbibition method. In this method a sample is immersed in a preferentially wetting fluid under vacuum for a sufficiently long time to let the fluid to imbibe into all the pores. The sample is weighed before and after imbibition. These two weights, coupled with the density of the fluid, permit calculation of the pore volume. By knowing the sample's bulk volume and pore volume the porosity can be directly calculated. The samples were kept inside oven at 125ºC for several hours to make sure that they are completely dry and then weighed. Then each sample was immersed in water inside a vacuum chamber for 5 minutes and was weighed again.

The porosity value changes from around 20% in 300µm regular structures to about 60% in 500µm regular samples with a sensible difference between regular and random structures.

4. CONCLUSIONS

The initial work carried out has identified the SLM manufacturing process as suitable to manufacture aluminium sintered style heat pipes. In continuation of this project the pore radii of the porous samples will be analysed under electronic microscope. Then SLM machine settings will be specified to achieve the most optimum set of permeability, porosity, pore radii values and a second phase of prototypes will be manufactured for processing into functional heat pipes.
These heat pipe samples will go through proof and burst pressure testing, ammonia charging and thermal performance test process and life testing will be initiated. The results will be presented in future papers.

NOMENCLATURE

A: Cross sectional area of the porous sample, m^2
K: Bulk permeability, m^2
l: Porous sample length, m
ΔP: Hydrostatic pressure drop of the liquid along the length, l, of the sample, Pa
Q: Fluid volume flow rate, m^3/s
V: Fluid velocity, m/s
µ: Fluid dynamic viscosity, Pa.s (kg/m.s)

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