Application of additive manufacturing in the development of heat pipe technologies

Pratik Prakash Gupta[1], Kuan-Lin Chen[1], Kuan-Yu Luo[1] and Shung Wen Kang[1*]

[1] *Tamkang University, New Taipei City, Taiwan*
**Corresponding author email address: swkang@mail.tku.edu.tw*

Abstract

The ever-increasing demand on reliable cooling of devices are increasing with the advancements in technology, while the dependency on such devices is in the incline. Heat pipes are a pillar on extraction of heat from applications ranging from silicon cooling to space shuttle thermal management. The heat transfer devices are also made for specialty cases and should be tested to provide a satisfactory performance. The overall manufacturing and testing of heat pipes and accompanying devices requires multitude of industrial and intellectual resources, which in general also result in mounting cost and time. The efficiency in manufacturing the heat pipes are vastly improved by the advancements in Additive Manufacturing (AM) processes, while presenting the thermal and structural behavior on par or superior to general quality materials. Also the AM processes can be controlled dynamically based on design and use case scenario, which present the opportunity to achieve complicated designs in a continuous process without difficulty. In recent years the trend of using AM to make heat pipes or devices working in conjunction with heat pipes, has increased constantly. This study shows the recent developments and advancement made in the field of heat pipes, with the help of AM processes. The understating of the AM processes in regard to production time, production quality, material used and requirement of thermal performance can significantly improve the selection time in regard to future researches. This study provides a review of the several advances made in past around AM in terms of heat pipe production with a honed in approach towards the comparatives of all the variables.

Keywords: Additive manufacturing, Heat pipe, Different materials, Adversities

1. Introduction

In the recent years, management of heat has become an essential task to improve sustainability and performance of modern industries with the demand growing exponentially. The development of reliable heat transferring devices such as heat pipes (HPs) and heat exchangers (HX) to achieve the requirement for maximum thermal extraction, is in the minds of recent researchers. For past few decades the advancements in heat pipe technologies are in progress which is leading several operations to its full potential. The advancements in heat pipe technologies are due to the multitude of research done for different kinds of heat pipes (ex. LHP, PHP, Micro heat pipes etc.) and different methods of analysis (ex. Numerical analysis and simulation), being in continuous development [1]. The application which requires the utmost utilization of the heat transfer capabilities and flexible design, has to be electronics or silicon cooling specially with the advancements in powerful electronics in last couple of decades [1,2,3,4]. The major components in heat pipes for achieving the optimized working stage is selection of right working fluid and wick. The design of wick plays significant role in the overall performance of a heat pipe [2]. For preferred electronics cooling the size of heat pipes should also be in miniature scale and the wicks should also be developed to micro scale for best overall cooling performance [3]. Furthermore, the maximizing of cooling the silicon also provides micro scale flat heat pipes which can directly cool the silicon with higher effective surface area. Development and production of ultra-thin heat pipes (UTHPs) for use in electronic devices, specifically CPU cooling has also recently been discussed [4]. From the studies shown before mostly related to silicon and electronic cooling require the dimensions of both the heat pipes and wicks to be minimized with no compromises in actual capability and surface quality. Thus, the alternative of using Additive manufacturing (AM) is a great revelation for production of such niche devices.

Additive manufacturing represents the opportunity to create complex shapes and devices with precise structural properties [5-7]. The research done for creating the OHP using titanium metal alloy, shows the advantages of using SLM with no compromises in performance [5]. The realization of additive manufacturing as an alternative to create small and complex structures i.e., wicks and porous media, has pushed the innovative boundaries in regard to utilizing them in heat transfer devices [6-8]. The performance of heat transferring devices created with the SLM method outperforms from the traditional devices due to its specialized design for the job [9]. The advantages of SLM over traditional forms of manufacturing (ex. Molding and extrusion), with no compromise in speed and costs of production and larger range of material available shows it as an elusive substitute [9, 10]. Traditional heat pipes and loop heat pipes take advantages from the porous microstructure design created by SLM for the improvements of capillary performance [8]. Even modern applications such as the thermal managements of silicon, also improves from the fact that the heat transferring devices can be directly made in conjunction with them or specially made for them specific to their designs [11].

The application related to AM and specifically SLM have more advantages in special grade devices with thermal capabilities enhanced as well [12-14]. One of the applications of using SLM produced material to make a complex shape, was to make a hollow pipe pitot tube with multiple holes for optimum heat dispersion [12]. The materials used in SLM techniques were tested further to know their physical limitations during heat transfer was also a concern and lead to the analysis [15]. The studies related to discussion of using the AM method to produce designs with thermal and structural integrity was a topic of discussion for few years with various studies [16-19]. The SLM manufacturing system is also can be modified to use with the objective of CNC milling head. The process explained in the study is used as a hybrid system of machining with both SLM manufacturing and CNC milling [13]. The advantages of producing a smaller design with channel like structure to introduce fluid flow heat dissipation and heat transfer is discussed in another study; the devices are completely redesigned by including floe channels to increase thermal dissipation in various areas are a great new initiative [18]. The materials used in SLM are also flexible depending upon the use case [14]. Even devices like heat exchangers can be built with the process without harming the overall performance of the device [14, 19]. The surfaces produced by SLM processes are also comparable or improved from the generally used materials, in terms of roughness and smoothness [19]. The rough surfaces produced from the process can enhance the overall surface area and act like small channels to maximize the heat transfer in passive cooling devices. Even for the general use pipes the internal shape can be optimized to produce better heat transfer without reducing the flow characteristics and internal flow pressure to a problematic degree [20]. The biggest advantages for AM methods for producing heat transferrable surfaces/devices is the ability to make unachievable designs with similar or better performance even with extra cost is justified for special case and study of any special case requirements [11].

The main agenda of this study is to understand the past progress of studies made in this area, to further improve the understanding for future research. This study made a comparative analysis in terms of different processes, material used and utilization of the same. The selection of material and production speed are very fundamental things to be considered while using AM production, meanwhile the specialty counterparts of AM processes such as surface roughness in relation with the material and process speed are to be considered as well. This study provides a very focused analysis of the possible approaches in the heat pipe production or production of a thermal device in general using AM. While there has been a very few substrata of data available, this papers shines the light on the variables to be considered while starting the research in given field.

2. Material based comparison

The material selection for making a heat pipe arises a question of using copper as the material for it, as it is used for decades to make heat pipes. In terms of industry standards, copper is considered to be one of the best conducting materials with being inexpensive and showing adequate structural properties as well. The application-based usage related to heat transfer arises the question of using cooper as the base material to make thermal devices such as heat pipes, using the Additive manufacturing process. Although copper has been applied to be used in few additive manufacturing processes, the difficulties to use it moved the industry into other alternatives such as aluminum or Titanium alloys. One of the first use can be seen in a process related to SLM called direct metal laser re-melting (DMLR) utilized to make different parts and shapes from copper. The method discussed in the process makes a basic structure from putting copper dust and melting it layer by layer. This study fount that the specific power or energy density required for copper substrate is much higher than the stainless steel substrate, thus affecting the overall forming of melted particle size. This effect will significantly reduce the overall meting and create structures with lesser structural integrity [21]. Similar test was also conducted to use copper alloy in SLM process to check its workability and built part properties. The research was able to produce a thermally and structurally stable print using moderate power (800W) and good speed of production (600mm/s). The study said to reach a minimum thickness of 0.05mm with over 96% relative density, which showcase the overall usability in terms of making a heat transfer device. Further the test showed the method for generating better copper and alloy materials, need to compensate with the higher thermal conductivity of copper powder. This shows the copper powder although can be used to make the product, is challenging to deal with it [22]. The material copper is selected because of its thermal and electrical capabilities, which is also changed when it’s made by AM. The study of the properties showed the density and conductivity of printed material on par with the demands [23, 24]. The density was also improved with the technique used and speed of production. Although the copper structure making requires a minimum pitch distance with optimization of hatch pitch distance, the product with passable densities can be achieved [24]. The manufacturing of copper is also known to be not fully cooperative with the inputs and it is discussed in another studies. The using of copper resulted in a very porous material with less density than the actual copper. The manufacturing of the specimen also showed the difficulty in optimization and failed strategies for copper material [25]. Another study of the method is done later and found that by increasing the accuracy with lowered powered laser resulted in a material which although suffers from similar porosity problem but shows a great thermal and electrical conductivity with on par resistivity; to be used in electronic components [26]. The results obtained by several studies shows that the copper can be used as a building material in AM, but it has several issues which concern with higher porosity and difficulty to make a suitable end product with reliability. The end product does represent higher thermal conductivity and resistivity, which is usually associated with copper material. In theory and preliminary applications copper can be used to make specialty parts for a specific case but the properties like density, surface roughness and porosity are not as good as the traditional material use like aluminum or titanium alloys [27].

The discussion on the 3D printing of metals in the newer ages are based on the two main alloys used for manufacturing: AlSi10Mg and Ti6Al4V alloy. The debate to use and select which of these frequently used material depends upon many parameters. The structural and thermal abilities of the end product, roughness of the surface, size of end part, speed of production and power required for the laser, are few of the key points to be considered while selecting the material of AM. The research where the 2 types of material are compared made a couple of joints using them and tested the resulted part. The titanium alloy managed to get parts with better definition and surface roughness. Although there are few more criteria’s to be considered like the laser reflectivity, flowability during building and cost of manufacturing, in which the aluminum alloy can be used [28]. Another study was done to check the strength and fatigue of the materials made by AM. Both the titanium and aluminum alloy represented similar ductile yield and ultimate strength and are on par with conventionally made parts. The deciding factor of the built was more dependent upon the structure made, accuracy and porosity rather than the material made itself [29]. A detailed study is also done to check the microstructure and material properties of both the alloys. The titanium alloy presented a better surface roughness than the aluminum model, where the model is needed to sandblast in order to get smoother surface. In terms of strength the titanium alloy made structure needs to be heat treated in order to increase its hardness, whereas the aluminum alloy made structures show very minute change in heat treatment. Another important factor to be considered are porosity produced by AM process and how does it get affected after the process. The study finds that the titanium alloy can produce highly porous material which will reduce after post processing, meanwhile aluminum alloy also has similar properties but the post processing shows the combination of pores. Due to the lower melting point of aluminum alloy it is easier to combine them [30].

All the additive manufacturing processes use different material as base of the manufacturing. The chosen material is a significant factor to consider in getting the desired product with thermal and structural qualities intended of it. There are several different types of material used in the AM process based on the intended purpose.

2.1. Ti-6Al-4V

The titanium alloy is used in AM from the beginning of its trend start to develop in industrial level applications. The Ti-6Al-4V makes a product with high structural and thermal benefits even with high manufacturing power and cost requirements. The use of Ti-6Al-4V alloy in terms of heat pipes or heat transferring device has been shown in the manufacturing of a block Oscillating heat pipe designed for silicon cooling specifically [31]. The design can be achieved from layer-by-layer manufacturing of a closed loop with only single filling port.

There are also mentions of using titanium alloy in different heat transfer applications other than heat pipes or heat exchangers [32, 33]. There is mention of the titanium alloy being used in different methods of process engineering and its applications [32]. Another review for the additive manufacturing in terms of heat pipe technologies mention the use of Titanium alloy to make a heat pipe and other heat transfer devices [33].

2.2. AlSi10Mg

The use of Additive manufacturing has been in rise due to its uniqueness and ability to get unachievable designs. Another important factor of any AM process is considered from the ease of making the machines to which we can shape the designs. The challenge is mainly to find a material easy to melt with lower powered laser and easily malleable. The choice of latest material for making heat transfer devices is AlSi10Mg, because of its lower melting point and excellent thermal and structural tolerances. One of the first cases of using AlSi10Mg, is to make microstructure of a finned shape to observe nucleate pool Boling effect from cooling to measure its effectiveness [6].

The use of AlSi10Mg is also in trend with recent publications with using them in thermal applications also increased. The use of AlSi10Mg to make a heat sink to improve the thermal performance in high heat output electronic application was studied with the visible improvements in heat transfer [9].

The mention of the use of aluminum alloy over the conventional metals is shown in the review of thermal energy conversion devices such as heat exchanger or heat sinks [10]. The use of AlSi10Mg to make a flat plate pulsating heat pipe was done with the test for detecting the heat removal capabilities with also consideration of surface roughness [34]. Also for specifically the heat exchanger the use of aluminum alloy is studied briefly and mentioned its benefits [35]. The use of aluminum to make flat plate heat pipes is also studied for the application of cooling LEDs and shown to be effective [36]. By using the additive manufactured part with the heat pipe to dissipate heat is also a consideration. The hollow structure made from Aluminum alloy for a specific case of cooling jet engines also shows the stability and high thermal conductivity of the produced parts [37].

The recent and old reviews also mention the use of material for AM [9, 10, 19, 33].

2.3. Stainless steel

The material which most associated with manufacturing is stainless steel and it has also been in consideration to be used in the Additive manufacturing. The material is cost effective although the surface quality is harder to achieve. For the lower cost applications such as the cooling of Led lights it is a useful material and has been tested. A loop heat pipe was built with the stainless steel by AM and used to cool the LED lights with a much better effectiveness to normal metals [38]. There is also a study to make the wick structure of heat pipe with stainless steel AM. The structure was made to test for capillary effect which can be applied to heat pipes [39]. Another recent study was based on making the stainless-steel wicks with Am for using in loop heat pipes. The study focused on making the LHP to be used in chemical plants and the overall product showed much better efficiency [40].

The trend of using steel in the additive manufacturing is mostly done for wick design in heat transfer devices. Another study has been done for wick structure of flat plate heat pipe. The study shows improvements of the wick structure in terms of phase change characteristics of the FHP with also increased heat transfer [41]. The review papers also mention the use of stainless steel.

2.4. Polycarbonate

The use of polycarbonate which has a very low thermal conductivity is mostly done to make some support structures and insulations. In their use of AM the use is with the heat transfer device to make a complex shape with any other conductor. The use of polymer to make a support structure for the copper heat pipes was tested with the effect of material as mostly insulator [42]. Another recent study used the polycarbonate material to make a flat plate using AM. The study was based on the visualization and flow effect of the PHP with the transparent plate. The material is defiantly useful to see and observe of a process because it is an insulator and doesn't affect the heat transfer in huge way [43].

There are a bunch of studies conducted by Koito et.at. in few years related to heat pipes, while using polymer substances as the base of additive manufacturing. One of the first works started by making an acrylic heat pipe from resins on top of steel structure to realize and confirm the behaviors of the thermosyphon. The printed structure was directly made on the resin board [44]. The same kind of methodology is used to make a sintered wick inside of the pipe for capillary behavior. The heat pipe with the wick structure put separately was printed also on the board itself [45]. The next application was to print a vapor chamber on the board and it was also build with the same resins with the dimensions of vapor chamber made to cool the electronics [46]. The research led to build the PHP using polymer components in conjunction with metal parts. The design was made to test the performance and behavior of the PHP [47]. The same PHP structure was used to visualize the flow pattern and behavior of the vapor forming and liquid slug flowing in the PHP during operation [48]. All the devices made by the researcher was not meant to break the barriers in performance, although it showed the behavior similar to the working heat transfer devices. Review papers mention polymers to be useful for designing and preliminary testing.

2.5. Other

There is a study based on using a PCB building material to be made layer by layer with the heat pipes or heat extractors in between the layers. The layers were printed and tested with the heat pipes to show a very good method of silicon cooling [49]. There is also a study which uses resin (Epoxylite EIP4260 resin) to make different complex shapes of heat guides to be used in passively cooling the electronic machines such as wound motors [50].

3. Device based comparison

The devices which are made using AM for the purpose of heat transfer are generally OHP or PHP for cooling a constant heat emitting subject. Even there are very few actual devices made for either investigation and general use, the few case studies show the effects and advantages for AM in terms of producing such devices.

The first study was done to see the effectiveness of AM material in terms of direct contact cooling. The design is based on the thermal management of high heat flux cooling for CPUs or other silicones. The capacity measures from 500 to 1000kW/m2. The research for cooling this kind of devices lead to two phase-based coolers and heat pipes. The flat plate heat OHP seemed to be the better option considering the larger surface connection to the heat emitter which in general have a flat surface as well. Also, generally the flat plate OHP have one single loop going from end to end with all the flow pipes in parallel positions. The study created a design which uses the technology from AM to make the internal loop have both lateral and horizontal turns inside. The design also has only purpose built injection and pressure holes with compact shape, which is shown in figure 1. The compact block shape design makes it easier to cool a constant heat flux due to the loop of flow in an interconnected design, which have larger loop for cooling and heating as well [31].

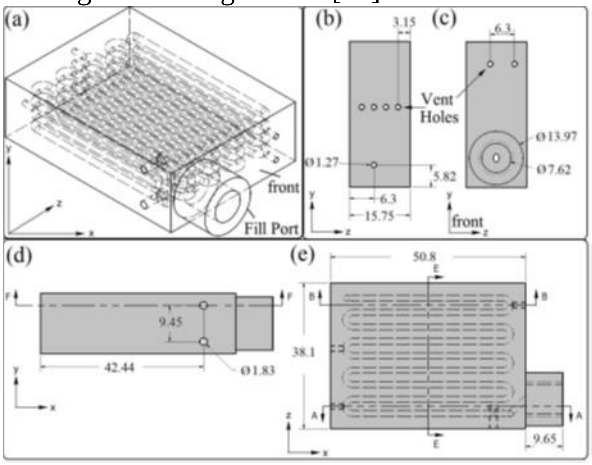

Figure 1. Design and internal pipeline representation of OHP made layer by layer using Ti-6Al-4V [31].

The device when made showed a reliable physical property such as density and surface roughness. The conducted experiments also provide a better insight on the thermal behavior of the built material and the device itself. The device shows a very good thermal ability with a very high thermal conductivity of 110 W/(m K), which is significantly higher than the base material- solid Titanium alloy (Ti-6Al-4V at 6.7 W/(m K)). Even the empty device showed the effective thermal conductivity of 18W/(m K), and shows the superiority of the solid material built by AM.

Another research by Ibrahim et.al.[51] was done with a similar device and using the similar base material (Ti-6Al-4V), in the AM process. It is also a block shaped OHP design with multidirectional interconnected loop inside. This device also has similar compact design and only few ports for filling and venting. The design of the device is shown in figure 2. This device is also made and tested for the intended purpose of cooling CPU or silicon of the flat surface with high heat flux emittance.

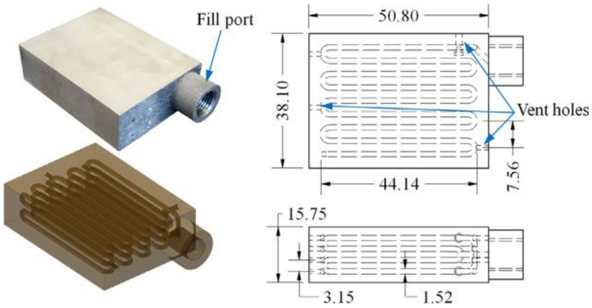

Figure 2. Ti-6Al-4V ML-OHP with fill port and vent holes: (top left) photograph after milling of faces, (bottom left) transparent view of channels in the part and (right) dimensioned drawings (in millimeters) [51].

The device was filled with Novac 7200 and tested for several factors to determine the performance with different orientations. The inside of the loop pipe shows a sintered wick like behavior with the working fluid and can be taken as a factor for reduced start up power. The built material shows no major flaw in the final design which would result in the blockage or reduction of performance. The device is tested with different orientation and with different filling liquids as well. The device which was tested empty showed the maximum thermal resistance and the thermal resistance of other tests are shown in figure 3.

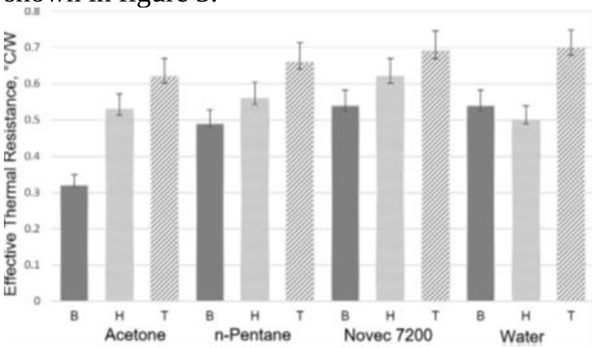

Figure 3.

Another study by Esarte et.al.[38] was focused on creating a loop heat pipe to cool an LED with the power output of 80W. The study focuses on building a wick structure using the AM technology and improving the performance of the loop heat pipe. The tests were done using different testing fluids as water and acetone for knowing the overall performance. The design and method of the wick was made for the best capillary structurer and water capillary performance required. The printing process and final product is shown in figure 4.

The final product has the porosity of 17% and shows a great capillary performance evaluated in the study. The capillary performance of the wick is compared in the figure 5, with different fluids.

The test results of the thermal conductivity and thermal resistance also shows a good in crease in performance with different heat load. The effect of fluid charge together with ambient temperature was finally addressed. A higher mass charge is preferable for higher heat loads and vice versa but considering critical restrictions regarding minimum and maximum fluid charge values, according to operative conditions, aiming to avoid excessively high operating temperatures inside the LHP. It was therefore finally charged with 22 g of methanol for our case study as was demonstrated in the previous section. the LHP that has been developed here can effectively control the operating temperature, and the LED junction temperature, under 100 °C for a representative heat load of 80 W, at different ambient temperatures, showing thermal resistance values of under 0.15 。C/W.

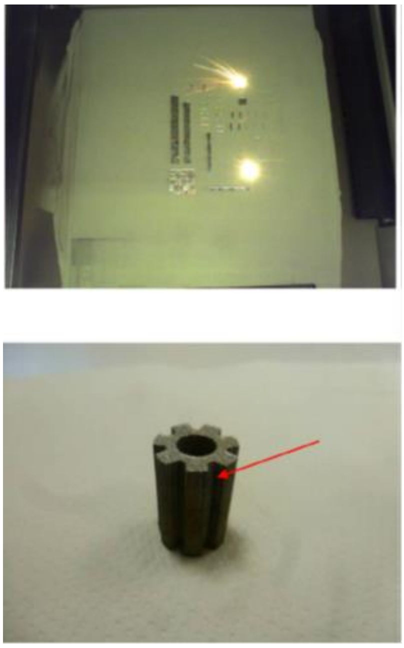

Figure 4. Fabrication of the primary wick, (a) printing procedure highlighting the laser points; (b) final result with a scaffold porosity of 17% [38].

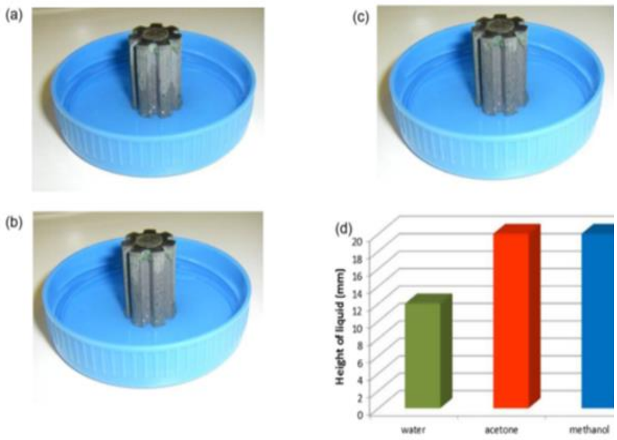

Figure 5. Capillary pumping test, (a) water rising up the primary wick after 5 min; (b) acetone at the top of the primary wick after 1 second; (c) methanol rising up the primary wick after 1 second; (d) comparative heights of the three fluids [38].

The test results of the thermal conductivity and thermal resistance also shows a good increase in performance with different heat load. The effect of fluid charge together with ambient temperature was finally addressed. A higher mass charge is preferable for higher heat loads and vice versa but considering critical restrictions regarding minimum and maximum fluid charge values, according to operative conditions, aiming to avoid excessively high operating temperatures inside the LHP. It was therefore finally charged with 22 g of methanol for our case study as was demonstrated in the previous section. the LHP that has been developed here can effectively control the operating temperature, and the LED junction temperature, under 100 °C for a representative heat load of 80 W, at different ambient temperatures, showing thermal resistance values of under 0.15 。 C/W.

The study done by Belfi et.al. [34] was focused on the development of a flat loop heat pipe using the DMLM (direct metal laser melting), by using aluminum alloy as the base material. The design of the LHP is shown in the figure 6.

The tests were done with same heating power of 200W and different cooling temperatures from 0 to -40 °C and two different filling ratios (50%,55%). Also, the test bench was tested horizontally and with 4-degree inclination. The results are based on the thermal resistance ratio (TRR), which should be as low as possible. The inclined setup and higher filling ratio of 55% showed lower TRR than the other equivalents. Overall, the design of the LHP showed a great promise for heat transfer performance and it can be adapted according to different requirements as well.

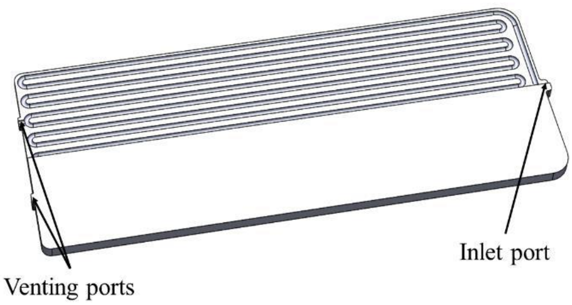

Figure 6. FPPHP CAD model used for the DMLM print job made with aluminum powder and layer resolution of 25 µm and 50 µm [34].

Another study is done on development of wick structure to be used in LHP by Hu et.al.[40] couple years ago, where he studied the effect of 3D printed wick structures with different hole sizes for the mesh. The structures made are very similar to wire mesh, typically used in stacks to produce the structure. The design made by the additive manufacturing is shown in figure 7.

The difference in the hole sizes changes the porosity and the overall heat transfer ability of the wick structure. The study states the heat transfer coefficient is highest and permeability is lowest for the small hole sample and vice versa for the large holes. The samples were put inside of the LHP and tested with same heat loads of varying degrees. The results showed that the sample with median hole size which has permeability and effective thermal conductivity of 2.13*10-10 m2 and 5.38 W/(m K) respectively, showed the most stable behavior and presented the best heat transfer coefficient and lower thermal resistance even in higher loads. The study showed a way of making the porous structure based on changing the hole size, which is an effective way of making the mesh of LHP with the entire properties depending on the hole size specification. For future studies the structure will be a good baseline to achieve the optimum mesh structure.

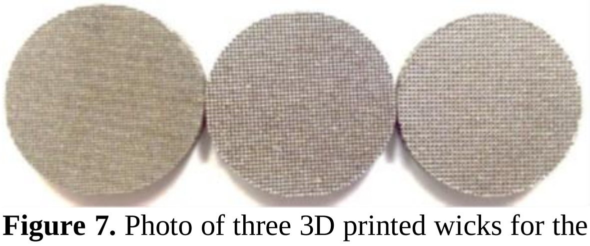

Figure 7. Photo of three 3D printed wicks for the experiment (from left to right Samples A, B and C) [40].

There are couple of studies done by Jafari et.al.[39, 41] in the year 2018 and 2020 on development of a wick structure in general heat pipe applications as well. The first study is based on the testing of the capillary performance of the additively manufactured wick structure. The study also tested with 4 different liquids and checked the rising in the wick structure over time. The properties of 3D printed wick was also tested with various studies where it's showed a better value of the parameters and predicted to be better at heat transfer abilities. The second study was based on the development and testing of a 3D printed wick structure of a flat heat pipe, based on the phase change heat transfer characteristics. The structure of 3D printed mesh is showed in figure 8 with the comparison with conventionally made mesh screens. The figure shows that the design made by 3D printing has similar basic structure with non-smooth outer shapes. The wick made by additive manufacturing showed slightly higher thermal capabilities that the normal screen counterpart.

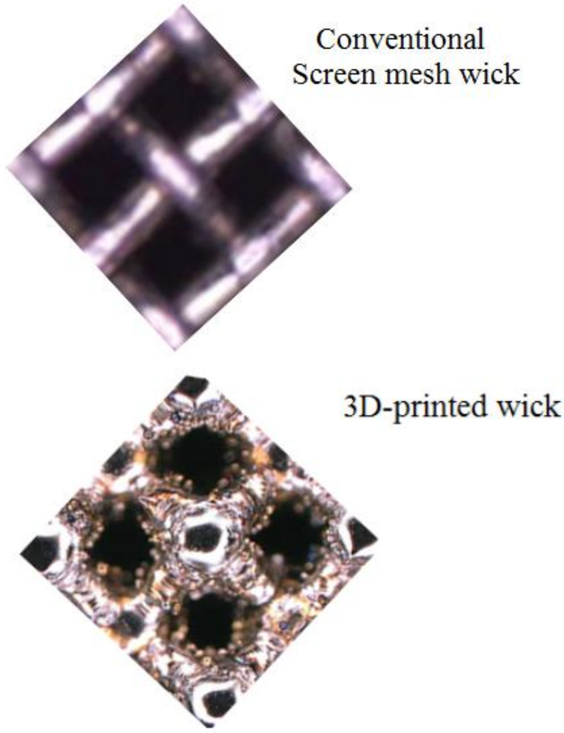

Figure 8. manufactured part pore shape and size compared to conventional screen mesh wicks [41].

Another study on the wick structure is done by Kaur et.al. [19] to be used in heat exchanger. The study is a review of all the lattice structures used in heat exchanger or similar operations, by

Table 1. Structural and Thermal properties of resultant product in terms of the build material during additive manufacturing.

Author	Process	Material	Type of the device	Speed of production	Product roughness	Thermal resistance	Thermal conductivit y	Relative thermal conductivity ratio
Thompson et.al.	SLM	Ti-6Al-4V	Flat plate OHP	70µm thickness with 400mm/s scanning rate	40% of stainless steel		110W/mK	16.41
Ibrahim et.al.	PBF	Ti-6Al-4V	Multilayer OHP	40cm/s scanning rate	Variation of 80µm from place to place	0.32-0.7°C/W From different filling liquid	110W/mK	16.41
Esarte et.al.	SLM	Stainless steel	LHP (wick design)	20-75µm thickness with max 10m/s scanning speed	Minimum feature size 150µm	Max. 0.15°C/W	1.48 W/m K	26.9
Belfi et. al.	DMLS	AlSi10Mg	Flat plate PHP	20cm^3/h max scan speed	25µm layer – 2.0533µm 50mm layer – 25.8160µm	Thermal resistance ratio down by 10%		
Hu et.al.	SLM (similar process)	316 stainless steel with other metals	LHP (wick)	20µm thickness with maximum 10m/s scanning speed		Minimum 0.031 for sample B	Sample A-8.63W/mK Sample B-5.38W/mK Sample C-4.06W/mK	172.6 107.6 81.2
Ho et.al.	SLM	AlSi10Mg	1*1cm^2 microstructure	550 mm/s	8.5µm		H = 0.7w/cm^2	
Jafari et.al.	SLM	Stainless steel	Wick to use for Heat pipes	Laser scan speed 7m/s	7.8~53.9µm			
Handler et.al.	PBF	AlSi10Mg and Ti-6Al-4V	Heat exchangers		15.68µm		110W/mK	16.41
Jafari et.al.	SLM	Stainless steel	Wick of FHP			Max 0.36°C/W	Max 820W/mK	122.38
Chao et al.	SLM	aluminum	FHP (Grooves)	300mm/s	Less than 25µm	Max 7°C/W		

considering the process of study and evaluation the different designs used. The different studies showed in the advantages of using additive manufacturing for making the design of the lattices used for their individual studies. The review done let us know that the additively manufactured lattices may result in significantly higher coefficient of heat transfer as compared to conventionally used metal foams. With the freedom of making multiple design adjustments allows different porosities through which higher effectiveness and thermal conductivity of device is to be expected.

The papers are also compared with the results and -abilities of the manufactured parts in Table 1. The analysis in Table 1 can also compare the working range and resultant workability of all the devices as well.

4. Nature of additive manufacturing related to heat pipe manufacturing

The additive manufacturing is the future of making the special grade or special designs in heat pipe. With the advantages of the technology, there are still some challenges and precautions to keep in check if we are making the products. The study of different additive manufacturing technologies gives us the idea about the adversities related to designs and maintaining the criteria to create the final product in which the adversities are minimized. There are few things and procedures which needed to be evaluated during and after the manufacturing process, to create a safe and specified final product. Some of the points which are very important to keep in mind when we are making the heat pipes from additive manufacturing are discussed here.

4.1. Investigation for the abnormalities inside the heat pipe-

There are many possibilities for the imperfections and abnormal structures formation, in terms of additive manufacturing in general. When it comes to the heat transferring devices such as heat pipes where we need to make sure the internal structure is functional as well as in accordance to our required task. The main requirements of a heat pipe come with the vacuum and fluid holding capacity of the final design. The main problem to worry about the final products are to find the trapped powder and cracks inside of heat pipe. The cracks which can create the gap in the wall of heat pipe and can prevent it from being sealed altogether. The heat pipes with cracks even when they are functional holds a serious threat to the operational life and conditions of the heat pipe. The crack can loosen and deteriorate the wall slowly in high heating condition which is a main drawback if we are considering the working environment of heat pipes. The determination of where the cracks form and which variables control them is a very important part of the study in achieving a satisfactory final device. There is another main concern about the powder being trapped in the final product due to the additive manufacturing being a layer by layer creation method. The powder inside the product can be removed but sometimes due to the informal deigns on the internal of heat pipes; specially LHPs. The heat pipes made with additive manufacturing should be tested for the powder trapped inside to make sure the powder inside becomes negligible; this will give the working fluid inside the heat pipe chance to be purest and work the best of its abilities. There are few methods which can help us to inspect the cracks and powder trapped inside. The most commonly known method is to use the CT scan machine to check for the imperfections in the product and the test must only be conducted when the level of imperfections doesn’t generate a scarcity on the integrity of the product. The main agenda for minimizing the cracks and powder inside the heat pipes are to create a safe product which will not leak due to crack in high heat load. Even though the disadvantages of the powder trapped inside is not proven and needs further research, which can provide an insight to the positive and negative effects of such scenarios. We have done some CT scan with Phoenix Vtomex S240 machine of the model built for a LHP made from additive manufacturing using aluminum alloy as the base. The machine is equipped with a 180 kV/20 W high-power nano focus X-ray tube with best detail detectability of 0.2 micrometer as well as for 3D analysis of higher absorbing objects of up to 10 kg weight and 500 mm in diameter with micro CT. Figure 9 and figure 10 are examples of testing the product with a CT scan machine.

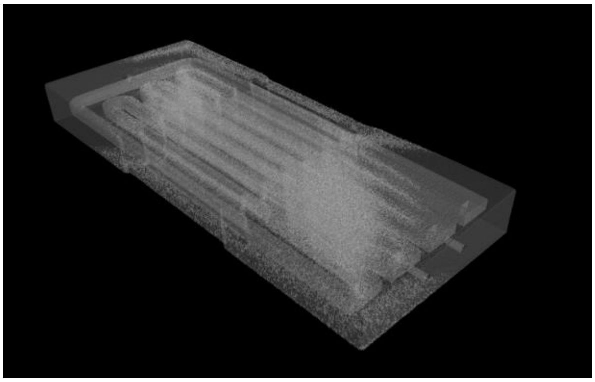

Figure 9. Inspection of Powder stuck inside the LHP using Phoenix Vtomex S240 CT scan machine.

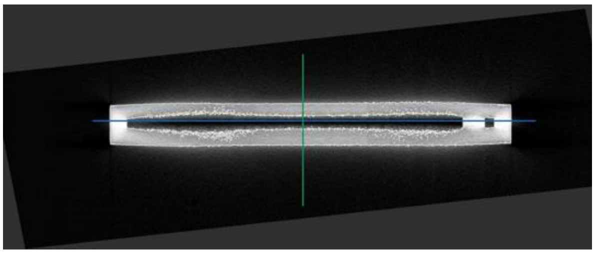

Figure 10. Cross section view of the LHP to show variation in internal surface (Phoenix Vtomex S240 CT scan machine).

Figure 9 shows us the overall design seen the scan machine and can tell us in case of trapped powder and cracks what are the percentages and where exactly to look at for finding such cases. The image shown does not have any serious crack or trapped powder; but in case of the cases happening, it will be visible with the bright spectrums.

Figure 10 is also a very subtle case of observation because of the size of device shown is too small. The device internal passage shows the imperfections and non linier boundaries with the particulate bumps. The crevices and bumps shown in the figure are now so significant but in some cases can create an abnormally behaving heat pipe or heat transfer devices. The boundary should be in the range of deviation from center and should not create a significant peak or valley.

4.2. Laser power and heat management-

Another very important variable is to keep in mind is that in additive manufacturing the overall conditions and input variable plays a significant roles in creating the perfect device. The two main input variables for controlling and determining the power to smoothness of final product surface are; laser input power and printing speed (hatch speed). The general specification of the speed and power of laser is dependent upon the size of device as well the base powder used for manufacturing. As we can generalize and observe the aluminum alloy requires less laser power than titanium alloy because of the melting points of both the powders. Even though the titanium alloy can produce smoother and cleaner surfaces; the high power from laser produces high heat which can damage or separate the layers of the production. This phenomenon can cause serious damage and render the final product unusable for the cause. Specially for the heat transfer devices the structure which is not strongly bonded can cause fatal accident and cause physical and monitory harm in the working environments. The devices are sometimes also used in special conditions such as space or vacuum; where the dangers of such become even greater. The heat output of the laser power should be minimizing to cause these kinds of harmful effects. The speed of the production should also be optimizing as the faster production speed can cause the product to not form properly and the slower productions peed can cause the product to lose its adhesive capabilities and not tie together.

For additive manufacturing techniques the scanning and hatching speed control depends upon the skin or layer formation of the structure and the size of skin can also be varied depending on the condition. The different kinds of skins or zones are determined during the slicing process at the start of production. Different zones in the slices of a part require different scanning and hatching strategies. This is because the solidified slices can interact with the solidified material in different ways. This is dependent on the thermal stresses inside and in between the slices, the desired material properties (for surface and volume of the parts), and the orientation of the parts on the platform.

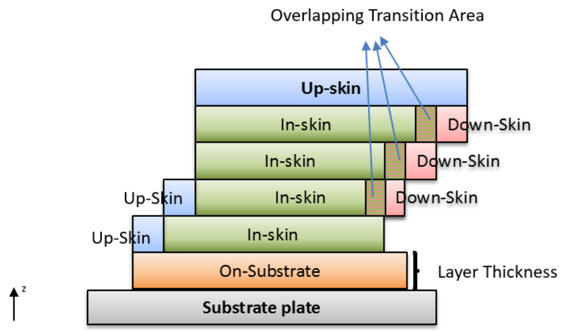

Figure 11. The skin formation shown with illustration, taken from Tongtai User manual Tongtai BP 1.0(For Tongtai AMP 160 3D printer).

In figure 11 the skin formation from the laser is given in detail and conjunction with the lower surfaces. The 'In Skin' is defined as the area between 'Up Skin' and 'Down Skin' areas. Defining an overlapping area between Down Skin and In Skin is used to ensure solid lamination of In Skin and Up Skin areas helping to avoid occurrence of tiny regions with untreated material. The Part Border is a contour that surrounds the fill area, e.g. In Skin, Up Skin and/or Down Skin. It defines the outer surface of the part. By controlling these parameters and understanding the power we can create an outer surface similar to that of conformal manufacturing techniques.

Another problem was studied by Yap et.al. [52], who has shown the problem of thermal fluctuations and the how it can form cracks. The study reviewed several other authors and determined the final product can produce crack or notable damages due to this effect. The study also includes the thermal gradient mechanism by Kempen et.al [53], which shows the crack formation and separation of layers in figure 12. More recently, Yasa et al. [54] introduced "sectorial scanning" as a scanning strategy in SLM. This strategy breaks down a layer into small square grids and neighboring grids are scanned perpendicular to one another. It was found that "sectorial scanning" is able to reduce the residual stress significantly. This strategy is now available in processing software, such as Autofab or SLM Build Processor and is known as chessboard strategy.

The problem of crack formation and delamination is especially prevalent in ceramic materials. Ceramics require very high melting temperatures and have very low thermal conductivity, resulting in very high thermal gradient during the process.

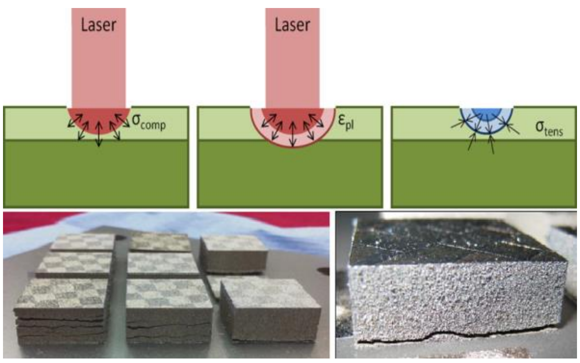

Figure 12. Temperature gradient mechanism (top) leading to crack formation and delamination (bottom). (Reproduced by Yap et.al. [52] with permission from Kempen et.al. [53] at an joint effort.)

4.3. Control of the manufacturing parameters-

There are some parameters which are also important for the final production of heat pipe devices and other structures. The main parameter which should be kept under some specifies condition is density of production. Some cases may require the light weight of the product but in case of heat pipes; the quality of material is significantly more important. The density can make a very big difference when it comes to the vacuum capabilities of the LHP and if it is not up to par ca cause failure of the device. The general case requires the relative density to be higher than 98% to be expected as better quality, but for some cases it should be even higher. For example, the LHP design created by us with different densities, had some difference in terms of packing of the overall structure. The situation is also experienced, where the part is printed using Tongtai AMP 160 3D printer. The LHP is printed with 94-96% density and is showing very high leaks even on the surface where the channels are not exactly beneath. The product develops a structure where, bubbles formed under water when the air is supplied to the LHP, also the pressure measured from the connected gauge also showed the pressure to be dropping over time. Also the surface of the LHP is forming the bubbles even at the points where the channels are not exactly under the holes. This phenomenon also presents the general failure of the packaging of the design. For the application such as LHP the tight packaging is required and the density should be higher. Another device is made by choosing higher density of 98.5%, which showed no leaks under water along with no pressure drop over time of two days in observation. We can say for the application of making heat pipes the density should be chosen at the higher end of spectrum; even it may increase the production time.

5. Conclusion

The study showed the developments and implementations of the AM techniques through different attempts and literature. The overall progress in Heat pipe production with AM has been continuously increasing throughout the years but can only considered to be in preliminary state. This study provides an insight on the way to approach for this topic with the aspects of selecting the right materials, the right methods, and the difficulties in production. By the overall consideration the future studies can be oriented into a path depending on the requirements of the study. We can deduce some guidelines based on the research done previously

- The constraints of design being a limiting factor on specialized devices, compels the additive manufacturing to be a feasible option. Even with the manufactured parts, the general properties seem on par to be used professionally.
- Various selection of materials to be used on different situations should provide a peace of mind, when using to make or to be used with the heat transfer device.
- There are several devices that can benefit from using additive manufacturing-based parts made from optimization through several refinements. The devices such as LHP, heat exchangers and thermal peripherals.
- There are several factors such as density of the product and quality of production, which impacts the final results and needs to be considered at each level of production. The adversities are also needs to be checked and based on the conditions and factors should be minimized for best output.

Acknowledgement

We would like to Thank National Science and Technology Council (NSTC), Taiwan, Republic of China, for supporting and funding the development of our research with project number 109-2221-E-032 -014 -MY2.

References

[1] Faghri, A.J.J.o.h.t., Review and advances in heat pipe science and technology. 2012. 134(12).

[2] Chan, C., et al., Heat utilisation technologies: A critical review of heat pipes. 2015. 50: p. 615-627.

[3] Chen, X., et al., A review of small heat pipes for electronics. 2016. 96: p. 1-17.

[4] Tang, H., et al., Review of applications and developments of ultra-thin micro heat pipes for electronic cooling. 2018. 223: p. 383-400.

[5] Monroe, J., et al. Thermal performance and surface characterization of a selective laser melted flat-plate oscillating heat pipe. in 2015 International Solid Freeform Fabrication Symposium. 2015. University of Texas at Austin.

[6] Ho, J.Y., et al. Enhanced nucleate pool boiling from microstructured surfaces fabricated by selective laser melting. in International Conference on Micro/Nanoscale Heat Transfer. 2016. American Society of Mechanical Engineers.

[7] Jafari, D., W.W. Wits, and B.J. Geurts. An investigation of porous structure characteristics of heat pipes made by additive manufacturing. in 2017 23rd International Workshop on Thermal Investigations of ICs and Systems (THERMINIC). 2017. IEEE.

[8] Esarte, J., et al., Performance assessment of a three-dimensional printed porous media produced by selective laser melting technology for the optimization of loop heat pipe wicks. 2019. 9(14): p. 2905.

[9] Wrobel, R. and A. Hussein. Design considerations of heat guides fabricated using additive manufacturing for enhanced heat transfer in electrical machines. in 2018 IEEE Energy Conversion Congress and Exposition (ECCE). 2018. IEEE.

[10] Jafari, D., W.W.J.R. Wits, and S.E. Reviews, The utilization of selective laser melting technology on heat transfer devices for thermal energy conversion applications: A review. 2018. 91: p. 420-442.

[11] Azizi, A., et al. Additive laser metal deposition onto silicon for enhanced microelectronics cooling. in 2019 IEEE 69th Electronic Components and Technology Conference (ECTC). 2019. IEEE.

[12] Fasano, M., et al., Passive heat transfer enhancement by 3D printed Pitot tube based heat sink. 2016. 74: p. 36-39.

[13] Liu, C., et al., Development and experimental validation of a hybrid selective laser melting and CNC milling system. 2020. 36: p. 101550.

[14] Hein, L., M.J.I.C.i.H. Mortean, and M. Transfer, Theoretical and experimental thermal performance analysis of an additively manufactured polymer compact heat exchanger. 2021. 124: p. 105237.

[15] Ding, X. and L.J.J.o.M.P. Wang, Heat transfer and fluid flow of molten pool during selective laser melting of AlSi10Mg powder: Simulation and experiment. 2017. 26: p. 280-289.

[16] Niknam, S.A., M. Mortazavi, and D.J.T.I.J.o.A.M.T. Li, Additively manufactured

heat exchangers: a review on opportunities and challenges. 2021. 112(3): p. 601-618.
[17] Nafis, B.M., et al., Additive manufacturing for enhancing thermal dissipation in heat sink implementation: A review. 2021. 42(12): p. 967-984.
[18] Zhang, C., et al., Additive manufacturing of products with functional fluid channels: A review. 2020. 36: p. 101490.
[19] Kaur, I., P.J.I.J.o.H. Singh, and M. Transfer, State-of-the-art in heat exchanger additive manufacturing. 2021. 178: p. 121600.
[20] Moon, H., et al., Heat transfer enhancement of single-phase internal flows using shape optimization and additively manufactured flow structures. 2021. 177: p. 121510.
[21] Pogson, S., et al., The production of copper parts using DMLR. 2003.
[22] Zhang, D., Z. Liu, and C. Chua. Investigation on forming process of copper alloys via Selective Laser Melting. in High Value Manufacturing: Advanced Research in Virtual and Rapid Prototyping: Proceedings of the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping, Leiria, Portugal. 2013.
[23] Raab, S.J., et al., Thermal and electrical conductivity of 99.9% pure copper processed via selective electron beam melting. 2016. 18(9): p. 1661-1666.
[24] Ikeshoji, T.-T., et al., Selective laser melting of pure copper. 2018. 70(3): p. 396-400.
[25] Silbernagel, C., et al., Electrical resistivity of pure copper processed by medium-powered laser powder bed fusion additive manufacturing for use in electromagnetic applications. 2019. 29: p. 100831.
[26] Kruth, J.-P., et al., Lasers and materials in selective laser sintering. 2003.
[27] Calignano, F., et al., Direct fabrication of joints based on direct metal laser sintering in aluminum and titanium alloys. 2014. 21: p. 129-132.
[28] Nalli, F., L. Cortese, and F.J.E.F.M. Concli, Ductile damage assessment of Ti6Al4V, 17-4PH and AlSi10Mg for additive manufacturing. 2021. 241: p. 107395.
[29] Ishfaq, K., et al., A state-of-the-art direct metal laser sintering of Ti6Al4V and AlSi10Mg alloys: Surface roughness, tensile strength, fatigue strength and microstructure. 2021. 143: p. 107366.
[30] Shi, L., et al., Evolution of multi pores in Ti6Al4V/AlSi10Mg alloy during laser post-processing. 2021. 176: p. 111109.
[31] Thompson, S.M., et al., Additive manufacturing of heat exchangers: A case study on a multi-layered Ti–6Al–4V oscillating heat pipe. 2015. 8: p. 163-174.
[32] McDonough, J.J.T.S. and E. Progress, A perspective on the current and future roles of additive manufacturing in process engineering, with an emphasis on heat transfer. 2020. 19: p. 100594.
[33] McGlen, R.J.J.T.S. and E. Progress, An introduction to additive manufactured heat pipe technology and advanced thermal management products. 2021. 25: p. 100941.
[34] Belfi, F., et al., Space structures with embedded flat plate pulsating heat pipe built by additive manufacturing technology: development, test and performance analysis. 2019. 141(9).
[35] Handler, E., et al. Design and process considerations for effective additive manufacturing of heat exchangers. in 2017 International Solid Freeform Fabrication Symposium. 2017. University of Texas at Austin.
[36] Chang, C., et al., 3D printed aluminum flat heat pipes with micro grooves for efficient thermal management of high power LEDs. 2021. 11(1): p. 1-8.
[37] Wu, F., A.M. EL-Refaie, and A.J.I.T.o.I.A. Al-Qarni, Additively manufactured hollow conductors integrated with heat pipes: design tradeoffs and hardware demonstration. 2021. 57(4): p. 3632-3642.
[38] Esarte, J., et al., Optimizing the design of a two-phase cooling system loop heat pipe: Wick manufacturing with the 3D selective laser melting printing technique and prototype testing. 2017. 111: p. 407-419.
[39] Jafari, D., W.W. Wits, and B.J.J.A.t.e. Geurts, Metal 3D-printed wick structures for heat pipe application: Capillary performance analysis. 2018. 143: p. 403-414.
[40] Hu, Z., et al., Development of a loop heat pipe with the 3D printed stainless steel wick in the application of thermal management. 2020. 161: p. 120258.
[41] Jafari, D., W.W. Wits, and B.J.J.A.t.e. Geurts, Phase change heat transfer characteristics of an additively manufactured wick for heat pipe applications. 2020. 168: p. 114890.

[42] Cage, K., et al. Thermal Design and Testing of a Passive Helmet Heat Exchanger With Additively Manufactured Components. in International Manufacturing Science and Engineering Conference. 2018. American Society of Mechanical Engineers.

[43] Arai, T. and M.J.A.T.E. Kawaji, Thermal performance and flow characteristics in additive manufactured polycarbonate pulsating heat pipes with Novec 7000. 2021. 197: p. 117273.

[44] Koito, Y., H. Maehara, and T. Tomimura. Fabrication of Heat Pipes on an Acrylic Resin Board. in International Electronic Packaging Technical Conference and Exhibition. 2013. American Society of Mechanical Engineers.

[45] Koito, Y., et al. A Capillary-Wick Heat Pipe Fabricated on a Plastic Board (Fundamental Experiments on Heat Transport Characteristics). in International Electronic Packaging Technical Conference and Exhibition. 2015. American Society of Mechanical Engineers.

[46] Hideyama, F., et al. Fabrication of a Vapor Chamber on a Plastic Board. in International Electronic Packaging Technical Conference and Exhibition. 2015. American Society of Mechanical Engineers.

[47] Koito, Y. and M. Kawaji. Performance of a pulsating heat pipe fabricated with a 3-D printer. in Heat Transfer Summer Conference. 2017. American Society of Mechanical Engineers.

[48] Arai, T., M. Kawaji, and Y. Koito. Visualization of Two-Phase Flow in 3D Printed Polycarbonate Pulsating Heat Pipe With Aluminum Substrate. in International Conference on Nanochannels, Microchannels, and Minichannels. 2018. American Society of Mechanical Engineers.

[49] Muthu, V., et al. Embedded thermal management solution for power electronics PCB using additive manufacturing. in 2017 Asian Conference on Energy, Power and Transportation Electrification (ACEPT). 2017. IEEE.

[50] Wrobel, R. and A.J.I.T.o.I.A. Hussein, A feasibility study of additively manufactured heat guides for enhanced heat transfer in electrical machines. 2019. 56(1): p. 205-215.

[51] Ibrahim, O.T., et al., An investigation of a multi-layered oscillating heat pipe additively manufactured from Ti-6Al-4V powder. 2017. 108: p. 1036-1047.

[52] Yap, C.Y., et al., Review of selective laser melting: Materials and applications. 2015. 2(4): p. 041101.

[53] Kempen, K., et al., In Solid Freeform Fabrication Symposium Proceedings. 2013.

[54] Yasa, E., et al. Investigation of sectoral scanning in selective laser melting. in Engineering Systems Design and Analysis. 2010.