METAL ADDITIVE MANUFACTURING OF INTERNAL FLOW CHANNELS WITH POWDER BED FUSION PROCESSES
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Abstract
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**Metal Additive Manufacturing of Internal Flow Channels with Powder Bed Fusion Processes**

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This thesis studies the advantages, disadvantages and possibilities of additive manufacturing in making components with internal flow channels. These include hydraulic components, components with cooling channels and heat exchangers. Processes studied in this work are selective laser sintering and selective laser melting of metallic materials. The basic principles of processes and parameters involved in the process are presented and different possibilities of internal channel manufacturing and flow improvement are introduced.
1 INTRODUCTION

Additive manufacturing means building a part layer upon layer. 3D-CAD model is made and then divided into layers. Using this model, a part is made by building the layers one by one on top of each other. Due to layer by layer manufacturing, complex structures can be manufactured inside a part. Originally additive manufacturing (AM) was developed to make prototypes, but nowadays it can also be used to manufacture finished products and optimized parts. AM makes easier to produce geometrically complex parts with minimal need for process planning. As the part is made from layers the thickness of each layer defines how accurate the part is to the original model. The thinner a layer is, the closer the manufactured part is to the original design. Layer thickness also determines how quickly the part can be made and how much post-processing is needed. (Gibson, Rosen & Stucker, 2010, p. 1-2, 8-9.)

With additive manufacturing, a more clean and resource-efficient way of producing parts can be achieved. For example aircraft and power generation industries can benefit from AM parts. When manufacturing engine components for aircraft industry with traditional milling only as little as 10% of the initial block may be used in the final part. In additive manufacturing the unused powder can be recycled within the process. This way the waste output can be near zero. The parts can also be designed much more freely. This enables weight reduction and that way more economical final product. (Buchbinder et al., 2011, p. 271-272.)

Being quite new a process, the whole impact on the environment is still quite unknown because not very much research has been made. For example electricity use and material consumption has to be considered. (Le Bourhis et al., 2014, p. 26.)

One of the limitations of the powder bed fusion processes is the build rate. Even if almost 100% density parts can be manufactured, the build rates mentioned in a work found in a research done by Shleifenbaum et al. (2010, p. 163) ranged from 0,5 to 12 mm²/s which is significantly lower than in traditional milling. The powder can be melted faster if the laser power is increased but it leads to higher evaporation and lower final part quality. This can
be avoided using larger beam diameter but it will also lead to larger melt pool and reduced part accuracy. This is why cost efficiency of AM is not yet suited for series production. (Schleifenbaum et al., 2010, p. 162-168.)

1.1 Research problem
Additive manufacturing seems to be a valid new way of manufacturing full density machine parts. Mechanical engineering can profit from it but it still has a lot of limitations. Research done in the field of additive manufacturing regarding internal channels is quite specific and focuses on one type of part. Wider research is not either done or it is secret and this work aims to give broader perspective on additive manufacturing of hydraulic channels, cooling channels and heat exchangers.

1.1.1 Research questions
Research questions this work aims to answer are:
- Why is additive manufacturing better or worse than traditional methods when manufacturing parts with internal features?
- How does processing parameters influence the manufacturing process and how can the process be improved?
- How has additive manufacturing been utilized in parts with internal features in the last couple of years?

1.2 Scope
This work concentrates on manufacturing components with inner channels using metallic additive manufacturing processes. Powder bed fusion processes, for example selective laser sintering (SLS) and selective laser melting (SLM) are discussed in more detail. Limiting the topic like this, is based on possible advantages of additive manufacturing processes when making highly optimized parts with inner features and also because of personal interest on laser manufacturing processes. SLS and SLM were chosen because they are the basic processes used in additive manufacturing of metallic powders. In this work the basic principle of powder bed fusion processes and parameters it involves are shortly discussed. Also different kinds of components with channels are shown and advantages as well as disadvantages of manufacturing such components using additive manufacturing are discussed.
2 RESEARCH METHODS

This paper is done with literary research. Most of the scientific articles found in this paper are found in scientific online databases like Scopus and Science Direct. As much of the research as possible is done using scientific databases directly or with Google scholar to keep the material as scientific as possible. To make sure that the information used in the research part of this work is still valid, only quite recent journal articles are used. The general rule considering the age of the article is that in the basic process information ten years is the oldest information that can be used and more detailed information about processes and applications should be from articles no older than five years. The article analyser in Scopus shows what is also apparent when researching papers including additive manufacturing of components with internal flow channels. As can be seen in figure 1 the number of articles has been quite steadily rising with search terms “additive manufacturing” AND “channel” from year 2006.

Figure 1. Number of articles with search terms “additive manufacturing” AND “channel” (Scopus).
3 METAL ADDITIVE MANUFACTURING

This chapter is about metal additive manufacturing processes. Powder bed fusion processes are discussed and the basic working principle, equipment, parameters and their effects on the final part are reviewed.

3.1 Powder bed fusion processes SLM and SLS
Selective laser sintering was developed before laser melting and it is the first additive manufacturing process used commercially when talking about powder bed processes. It was developed for manufacturing prototypes from polymer materials but is now also used for metals, ceramics and composites when manufacturing finished products. The material properties achieved with metal powder bed fusion processes are comparable to engineering-grade metals. (Gibson et al., 2010, p. 103.)

Finding the optimal parameters in SLM and SLS is often complicated because many things affect the final quality of the part. (Wei et al., 2011, p. 189.) There are laser parameters, powder related parameters and layer parameters. The laser parameters include for example laser power and scanning speed, the powder parameters particle size and heat conductivity and the layer parameters for example the layer thickness. (Yadroitsev, Bertrand & Smurov, 2007, p. 8064.)

3.1.1 Selective laser sintering
Sintering indicates fusing the powder particles together without melting them. The mechanism in sintering is diffusion between particles. The particles diffuse together as the try to minimize their free energy by decreasing the total surface area of the particles. The sintering phenomena slows down when the surface area decreases. Due to process slowing down, the longer the processing time or the sintering temperature, the lower the porosity of the final part is. The sintering temperature have to be under the melting temperature of the material or the process will become laser melting. The working principle of a selective laser sintering machine can be seen in figure 2. (Gibson et al., 2010, p. 103-119.)
Smaller particle size means higher surface area to volume ratio and thus smaller particles sinter in lower temperatures and more rapidly that larger particles. Also when nearing the melting temperature, sintering becomes increasingly rapid due to increasing diffusion rates. Effects of heat in powder particles can be seen in figure 3. (Gibson et al., 2010, p. 105-106.)

Figure 3. As the surface area decreases so decreases the free energy. Powder particles try to minimize their free energy by increasing the neck size and decreasing the pore size throughout the sintering process (a to c). (Gibson et al., 2010, p. 106.)
3.1.2 Selective laser melting

Selective laser melting (SLM) differs from selective laser sintering because it uses a different binding process for the powder. With selective laser melting near 0 % porosity can be achieved resulting in full density metallic material from powder. Also compared to sintering only a little or no post-processing at all is needed. This is achieved by fully melting the powder particles. Negative effects of SLM are residual stresses in the part because of the higher thermal gradients caused by higher processing temperatures. They can in the worst case lead to distortions, cracking or delamination. Basic working principle of a selective laser melting machine is presented in figure 4. (Kruth et al., 2004, 616-619.)

![Figure 4. Working principle of an SLM machine (Gasser et al., 2010, p. 59).](image)

3.1.3 Working principle if SLS/SLM equipment

Basic working principle of laser sintering and laser melting is basically the same, but with SLM a much higher energy density is required. (Casalino et al., 2015, p. 151.) A CAD model is divided into cross sections which are then individually constructed from powder. The part is built from powder as the laser beam scanning across the surface of the powder bed causes powder particles to melt or sinter together. (Simchi & Pohl, 2003, p. 120.)

After each constructed layer the build platform lowers and levelling system spreads a thin layer of powder on top of the previous one. This new layer is then sintered or melted and the process repeats until the part is finished. The loose powder serves as support for the part and
other support structures are not always needed. After the finished part has cooled, the loose powder is removed and finishing operations are performed. (Gibson, 2010, p. 104-105.) In the final part each layer consists of lines of molten or sintered powder. The quality of the part depends on the quality of each layer and each molten line. That is why finding the optimal parameters for the process is crucial. (Yadroitsev et al., 2007, p. 8064-8067.)

Even if the process is called sintering or melting, often parts from both of these binding mechanisms can be present in the process. This depends on the energy input to the process and the powder particle combinations. (Gibson et al., 2010, p. 113.)

3.2 Parameters
Scanning speed, laser power and spot size are the most important laser parameters in additive manufacturing. Other parameters involved in the process that can be controlled are layer thickness, scan spacing and powder properties. These parameters influence the melting phenomenon and must be optimized in order to achieve the best quality for the part. The combination of laser power and scan speed results in energy density. Energy density in the process can be increased by increasing the laser power while keeping scanning speed constant. Contour plot for energy density and relative density can be seen in figure 5. (Casalino et al., 2015, p. 152-156.)

![Figure 5](image)

**Figure 5.** Energy density (scan speed and laser power) compared to relative density of the part (Casalino et al., 2015, p. 157).
According to research by Casalino et al., (2015, p. 153-155) with 18 Ni Marage 300 steel, increased energy density results in increased relative density of the finished part. With higher energy densities the relative density of the part achieved using selective laser melting can be as high as over 99% of the density of the 18 Ni Marage 300 alloy. The high density parts in the test had only small closed pores with regular shape whereas low density ones had large pores with irregular shapes. Pores affect the mechanical properties of the part and the fracture behaviour changes from fragile to ductile when the relative density increases. The stress-strain curves for different densities can be seen in figure 6. (Casalino et al., 2015, p. 153-155.)

![Stress-strain curve for 18 Ni Marage 300 steel with different relative densities of the finished part](image)

**Figure 6.** Stress-strain curve for 18 Ni Marage 300 steel with different relative densities of the finished part (Casalino et al., 2015, p. 155).

The hardness of the part is also comparable to energy density and higher hardness can be achieved with higher energy density. Maximum hardness of 34 HRC can be achieved which is the same as with wrought 18 Ni Marage 300 steel. The higher energy density also results in more effective melting of the powder which produces better surface roughness. The correlation of energy density with surface hardness and roughness can be seen in figure 7. (Casalino et al., 2015, p. 153, 156.)
Figure 7. Effects of energy density to hardness and surface roughness when using 18 Ni Marage 300 steel (Casalino et al., 2015, p. 156).

Thermal stresses can affect the dimensional accuracy of the part. Low scanning speeds and high cooling rates in the process can cause large thermal residual stresses which deform the part. With powder bed preheating, thermal deformations of the part can be reduced. Preheating can also lead to less porous material. Effects of preheating the powder bed on these properties can be seen in figures 8 and 9. (Zhang, Dembinski & Coddet, 2013, p.27-28.)

Figure 8. Effects of preheating to relative density of the finished part made from 316L steel (Zhang et al., 2013, p. 27).
In selective laser melting the layout of the parts also affects the mechanical properties than can be achieved. The non-uniform heat distribution and different cooling rates in the powder bed caused by different part layouts and gas flow differences can cause final part delamination. According to Dadbakhsh et al. (2012, p. 247) “In other words, laying the parts perpendicular to the gas flow (shorter length of part in direction of cooling) leads to a slower cooling and consequently less thermal stress and better bonding of additive layers in comparison with that parallel to gas flow.” When manufacturing cylindrical parts parallel to the gas flow, the gas movement causes lower temperature gradient to the other end of the part, which causes delamination and mechanical properties will decrease. The effects of part layout and gas direction to final quality of the parts can be seen in figure 10. (Dadbakhsh, Hao & Sewell, 2012, p. 243-248.)
3.3 Support structures

Powder bed fusion processes often require the use of additional structures to support the weight of overhanging geometries when the amount of overhang (Figure 11) exceeds a certain value (Calignano, 2014, p. 203). These structures connect the main part to the base plate and prevent distortions in the final part caused by thermal stresses. Without the support parts can also fail during the building process. (Hussein et al., 2013, p. 1024.) The support structures are sometimes unwanted as they increase manufacturing and post processing times. The build efficiency can be improved by designing the geometry of the structures self-supporting. Even if the overhanging structures are self-supporting, dross formation can occur in the lower edge of the part which is supported by the powder bed. This happens when the melt pool becomes too large and sinks into the powder as a result of gravity. With AlSi10Mg structures with overhanging angles between 30 and 45 degrees from the horizontal surface are self-supporting. Even if the parts can be build self-supporting, as the angle decreases the dross formation and surface roughness increases. (Calignano, 2014, p. 204-208, 211-212.)

Figure 10. Effects of part layout in delamination and final part quality (Dadbakhsh et al., 2012, p. 244).
In addition to supporting the part during the build process, they also have a role in removing the heat from the process. Design of the part is important as small changes in part orientation can help to reduce the need of support structures. (Järvinen et al., 2014, p. 73-74.)
4 TRADITIONAL MANUFACTURING OF INTERNAL CHANNELS

Traditional manufacturing method for producing internal channels, for example cooling channels in injection moulds, is CNC drilling. Straight channels are easy to produce with drilling but it is hard to manufacture cooling channels that are placed close to the mould wall for increased and uniform cooling performance. This way in complicated parts a non-uniform cooling is present so the cooling process for the moulded part is longer than with conformal cooling channels manufactured by additive manufacturing. With the help of 3D CAD models, even the drilled holes can be positioned so that optimized cooling can be achieved even if it is not as good as with conformal cooling channels. (Dimla, Camilotto & Miani, 2005, p. 1294-1300.)

Injection mould inserts often include a lot of components other than cooling channels such as ejector pins and sub-inserts (figure 12). Due to that the cooling channel route designing can be difficult, especially if they are produced with conventional CNC milling. When designing straight cooling channels it is also important to make sure they can be connected to form a patch for a coolant to flow between the inlet and the outlet. Methods for calculating the optimal configuration for the channels and other components inside the injection mould have been made, one of them being configuration space (C-space). It can help to calculate the best solution for design among all of the feasible designs. (Li & Li, 2008, p. 334-337, 347.)

Figure 12. Different components inside the injection mould tool (Li & Li, 2008, p. 335).
Conformal cooling channels can also be manufactured using conventional milling methods by milled groove insert method. In this method patterns are milled in the outside profile of the mould. Different kind of cross sections can be used depending on the tool shape. Cooling performance depends on the surface area of the cross section of the groove, this is why u-shaped cross-section is less efficient than rectangular. The groove pattern should be designed so that it does not interfere with components such as ejector pins in the mould. Figure 13 shows the cooling channels manufactured using milled groove insert method. (Sun, Lee & Nee, 2004, p. 717-719.)

Figure 13. Milled grooves (lighter areas) in the mould (Sun et al., 2004, p. 717).

Gun drilling or deep hole drilling is a valid way to produce deep and precise holes in metallic and other materials. Thus it is widely used process to create deep holes to components used in hydraulic applications (Biermann, Kersting & Kessler, 2009, p. 89). When drilling deep holes, lubrication and chip evacuation plays an important role in obtaining greater surface quality and tool life. Because poor removal of chips from the process can result in tool breakage, in gun drilling it is essential to remove as much of the chips from the process and due to that, dry machining cannot be used effectively in deep hole drilling processes (Biermann & Iovkov, 2013, p. 88). The gun drilling tools are often coated with material, for example titanium based hard coating, to ensure that previously mentioned attributes are achieved. (Wang et al., 2012, p. 200.)
Because gun drills are used in drilling long holes their shank length can be much longer than regular drills. Due to its length, the drilling tool has low stiffness and is susceptible to vibrations during the process, which can lead to worse performance of the drill. Some experiments have shown that frequency of the chip formation during the process causes the drill to vibrate. The amplitude of the vibration seems to be affected by cutting speed and feed. (Astakhov & Galitsky, 2005, p. 511-515.)
5 ADDITIVE MANUFACTURING OF INTERNAL CHANNELS

Additive manufacturing offers flexible production of complex internal shapes such as different kinds of flow channels. It does not require traditional tooling or moulds as the material is placed selectively only where it is needed. (Zhai, Lados & LaGoy, 2014, p. 808.) In the following chapters manufacturing of hydraulic components, cooling channels and heat exchangers is introduced.

5.1 Hydraulic components

Hydraulic applications is one valid way to utilize additive manufacturing. For example fluid flow in gearbox can be made smoother using additive manufacturing due to smoother channels in which hydraulic fluid flows. The weight of the gearbox can be also reduced as much as 30% and it will also change gear faster because there are no sharp corners for the fluid to go through. Hydraulic valve housing for Airbus A380 manufactured with traditional methods is also restricted to design for manufacturing principles but with additive manufacturing, the part can be designed to achieve the best strength and performance without the need for complex machining. (Roberts, 2012, p. 10.)

5.1.1 Examples of hydraulic channels

In a hydraulic crossing, two hydraulic fluids need to cross in a limited space without mixing with each other. The conventional solution is a heavy and large metal block where the holes for hydraulic fluids are drilled. The measurements of one conventional block are 230x230x50 mm and the weight is 20 kg. With additive manufacturing the fluid flow can be significantly improved due to optimized flow design thus greatly improving the performance of the part (figure 14). The new weight of the component can be reduced significantly, in this case, to only 0,7 kg and the measurements to 80x80x50 mm. The mass reduction with these optimizations is about 96 %. The new channel geometry means that the pressure loss with a flow of 100 l/min is only 20% of the one in the original design, even without any post-processing of the part. The new design can be seen in figure 15. (Isaza & Aumund-Kopp, 2014, p. 51.)
In racing and especially in Formula 1 the need for reduced component weight is crucial. Additive manufacturing can be used to reduce component weight and to improve performance. Titanium can be used when manufacturing hydraulic components for racing with laser sintering. Components can be manufactured so that no failure will occur during usage. Hydraulic Ti64 parts with 0.5 to 2 mm thick walls can survive pressures of 24 MPa without failure. Some pressure loss can happen in the first few minutes of usage but according to research done by Cooper et al., after that the pressure remains constant. The pressure lost possibly occurs in the system as it is present in all of the samples. With laser sintering the fluid flow can be also improved as seen in table 1. The pictures of the fluid channels can be seen in figure 16. (Cooper et al., 2012, p. 226-229.)
Figure 16. Fluid flow test traditional 1 (upper left) traditional 2 (lower left) compared to DMLS parts (upper and lower right) (Cooper et al., 2012, p. 228).

Table 1. Flow measurement comparison for traditional and DMLS manufactured channels (Cooper et al., 2012, p. 228).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Traditional (m/s)</th>
<th>DMLS-manufactured (m/s)</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exit 1</td>
<td>1,5</td>
<td>3,0</td>
<td>100</td>
</tr>
<tr>
<td>Exit 2</td>
<td>1,0</td>
<td>2,5</td>
<td>250</td>
</tr>
<tr>
<td>Exit</td>
<td>1,0</td>
<td>2,5</td>
<td>250</td>
</tr>
<tr>
<td>Centre</td>
<td>2,5</td>
<td>4,0</td>
<td>160</td>
</tr>
</tbody>
</table>

The faster flow achieved with AM means more kinetic energy is contained throughout the system resulting in lower energy input needed to achieve the same effect in operation. Research done by Cooper et al. shows that surface roughness without post processing in the part produced by AM was from 3,96 to 27,93 Rₐ µm. The roughness is relative to build orientation in the part and the roughest area was where the support structures for the part existed. It would be ideal that no post processing would be needed because good surface quality is important in hydraulic applications as it means smaller losses in efficiency. Expected range of porosity in the part was measured in the part and with titanium alloy over
99% relative density was achieved with only 0.28% porosity. The parts were stress relieved for 90 minutes in 790°C and naturally cooled in the furnace. After the heat treatment surface hardness of the parts was measured to be 500HV. The heat treatment increased the hardness from 350HV. In the test it was shown that laser sintering is capable of producing parts from titanium Ti46 that are geometrically accurate and mechanically capable. Geometrical complexity also allows opportunities to enhance performance of hydraulic systems in race cars without weight increase. (Cooper et al., 2012, p. 227-229.)

The optimisation in hydraulic actuator system for gear change manufactured with AM can be seen in figure 17. The original straight drilled holes for fluid are curved to improve fluid flow. The fluid channel cross-section is also designed so that fluid channels are self-supporting. The shape also enables smoother flow for the liquid. The weight savings can be so great that the part made of steel can weigh as little as the original aluminium part. The theoretical mass of the improved part is 28% of the original. (Gear change hydraulic actuator system.)

![Figure 17](image)

Figure 17. Cross section image of a gear change actuator. Left, original design, compared to improved design manufactured using DMLS, on the right. (Gear change hydraulic actuator system.)

5.2 Cooling channels
Before the usage of additive manufacturing cooling channel shape for example in injection moulding has been limited to a straight drilled hole. This limits the ability to distribute cooling where it is really needed in the process. With additive manufacturing, it is possible to build cooling channels that follow the contours of the tooling cavity in injection moulding. This is called a conformal cooling system. Conformal cooling system makes better
dimensional accuracy and reduced production cycle times possible. According to Boivie, Dolinsek and Homar (2011), up to 20 to 50% reduction in cycle times is possible dependent on the part dimensions. (Boivie, Dolinsek & Homar, 2011.)

With cooling channels better surface quality can improve the cooling properties of the channel. That is why internal finishing methods are important. One method reducing internal surface roughness uses free abrasive grains as a polishing agent. After the internal cooling channel is manufactured using AM techniques, a liquid with abrasive grains in it is run through the channel several times. The abrasive liquid cleans the channel surface from unstable powder residue thus improving the surface quality of the cooling channel. According to Furumoto et al. (2011, p. 1742) “the internal face roughness of the cooling channel improved significantly during the first 1000s of finishing.” (Furumoto et al., 2011, p. 1742-1748) The setup for internal cooling channel polishing can be seen in figure 18.

**Figure 18.** Experimental setup for cooling channel internal surface finishing (Furumoto et al., 2011, p. 1744).

Hydraulic cylinders move the abrasive liquid through the channel and it can be used again by reversing the pumping direction. The grain concentration used in the test done by Furumoto et al., is 4 volume-% and pressure of the liquid 1,4 MPa. In the test it was found that cooling time reduces by 4% as a result of the surface finish. This is explained due to the removal of powder particles, which cause rougher surface quality, from the cooling channel internal surfaces and it is an effective method for improving thermophysical properties in
cooling channels. Graph of finishing time compared to surface roughness can be seen in figure 19 and variation in internal face in figure 20. The cooling time comparison is presented in figure 21. (Furumoto et al., 2011, p.1743-1745.)

![Graph of finishing time compared to surface roughness](image1.png)

**Figure 19.** Finishing time compared to internal surface roughness (Furumoto et al., 2011, p. 1745).

![Surface roughness before and after abrasive treatment](image2.png)

**Figure 20.** Surface roughness before and after abrasive treatment (Furumoto et al., 2011, p. 1746).
5.2.1 Examples of cooling channels
According to EOS GmbH, a German manufacturer of AM parts and machines, laser sintering can make milling and EDM obsolete when complex part geometries are required in for example inserts. In addition to being a manufacturer of AM machines, EOS is working with companies to help improve economics and quality of the moulded parts. Manufacturing of cooling channels in a defined distance from a cavity is a key advantage of AM. It can be said that number of routing options compared traditional manufacturing are limitless. Advantages of AM compared to conventional drilling can be seen in figure 22. (Mayer, 2009, p 2-4.)

Figure 21. Time to room temperature before and after surface finishing treatment (Furumoto et al., 2011, p. 1747).

Figure 22. Cooling channels made by conventional drilling (left) compared to AM technique (right) (Mayer, 2009, p. 2).
Cooling channel cross sections can also be modified to create the smoothest flow through the entire channel. Actively switching between different channel cross sections throughout the channel is possible with AM and can help to control the turbulence of the coolant. Higher expected turbulence in the channel can increase the cooling performance. With laser sintering cooling channels with complex shapes and diameters down to 1mm can be achieved. One rule choosing the channel shape is that it should be self-supporting. This means that overhanging areas should be angled more than 40 degrees to horizontal. Self-supporting channel design can be seen in figure 23. Ribbed shape of the channel surface, as seen in figure 24, can increase the cooling performance in the channel by generating wanted turbulence in the cooling liquid. (Mayer, 2009, p. 7-8.)

**Figure 23.** Easier manufacturing due to self-supporting geometries in internal cooling channels (Mayer, 2009, p. 8).

**Figure 24.** Example of ribbed cooling channel to increase cooling performance (Mayer, 2009, p. 8).
Studies done by EOS have shown many benefits for conformal cooling channels. Research done with PEP – Pôle Européen de la Plasturgie achieved 20 second reduced cycle time by reducing tooling temperature by 20°C. With LBC – LaserBearbeitungsCenter cycle times could be reduced down to 60% of the original. Also the scrap rate could be dropped from around 50% to zero by optimizing tooling temperatures. Cooling channels design differences in the research done with PEP can be seen in figure 25. (Mayer, 2009.)

![Figure 25](image)

**Figure 25.** Conventional cooling channels (left, red channels) compared to solution achieved by additive manufacturing (right, green channels) (Mayer, 2009, p. 5).

The cooling channels are also made in the mould at the same time as the mould is produced compared to conventional design where the channels need to be drilled afterwards. This simplifies the manufacturing process. The real challenge is to find the correct design for the cooling channels in the first place. (Mayer, 2009, p. 5-6.)

Conformal cooling channels do not always reduce cooling times or otherwise shorten the manufacturing times. Although in the test performed by Norwood et al., (2010, p. 669-671, 674-678) the part with conformal cooling was approximately 20°C cooler than traditionally manufactured and the surface area and the volume of the cooling channel was 1.5 time the original, the solidification time with aluminium did not improve. According to Norwood (2010, p. 678) “This may be due to the shape, surface area, volume, flow rate and or location of the cooling channels being inadequate.” The cooling could be increased by redesigning the cooling channel. Turbulent flow or positioning larger channels closer to tooling area might increase the cooling effect. The tool and its cooling channels can be seen in figure 26. (Norwood et al., 2010, p. 669-671, 674-678.)
5.3 Heat sinks and heat exchangers

Additive manufacturing makes manufacturing complex structures that can be used effectively in heat exchangers possible. For example extremely tight spaces and complicated tilting in the part can make the part impossible to manufacture using milling or casting by preventing access for tools and mould removal. (Wong et al., 2007, p. 292-296.)

Heat transfer is dependent on thermal properties of the material, mainly thermal conductivity, and the surface area. With additive manufacturing large surface areas can be achieved for example by creating grid-like mesh structures or random foam structures. In figure 27, different foam and mesh structures fabricated using additive manufacturing can be seen. (Ramirez et al., 2011, p. 5379-5382.)
5.3.1 Examples of heat exchangers

Heat pipe based heat exchangers are used in space crafts and have to go through relentless testing before they can be used in real life applications because if something fails in space, it can’t be fixed in most cases. Use of additive manufacturing in these applications is also researched. Currently available aluminium ammonia heat pipes are manufactured using extrusion, but with SLS/SLM processes some advantages can be achieved. Different, very complicated, wick structures can be manufactured inside the heat pipe. The wall of the heat pipe is solid with the porous wick structure layering the inside of the wall. When using SLS/SLM the pipe can be constructed with a single manufacturing stage. The wick layering inside of the wall is made so that it forms the capillary structure in the pipe. This structure helps to transport the liquid inside the pipe between the evaporator and the condenser sections of the pipe. The inner structure of the pipe can be seen in figure 28 and it can have different porosity and thickness depending on the part of the pipe it is used. (Reay, Kew & McGlen, 2014, p. 105-123.)
Figure 28. Internal wick structure of a heat pipe made by SLM. Outer diameter is 14 mm and the length 70 mm. (Reay et al., 2014, p. 122.)

5.4 Patents

A large number of patents can be found filed in recent years that include additive manufacturing of components with some internal constructs that help cooling the part. These patents often suggest that these features cannot be made with other manufacturing methods.

Additive manufacturing makes very efficient design in turbine blade cooling channels possible (Pat. US 20140140859 A1, 2014, p. 1-3). With additive manufacturing cooling channels can be manufactured inside a turbine blade (figure 29). Usually the turbine air foil structures are manufactured using die casting. Die casting method limits the geometry, size and location of internal structures that can be manufactured. These limitations can reduce the performance of the airfoil part. With additive manufacturing a lattice network can be manufactured inside the airfoil. With internal cooling the blade can also manage higher temperatures or operate longer in lower temperatures that a blade with no internal cooling. (Pat. US 20130276461 A1, 2013, p. 1-5; Pat. US 20140169981 A1, 2014, p. 1-3.)
Figure 29. Turbine blade internal cooling channels (Pat. US 20140169981 A1, 2014, sheet 5).

After manufacturing the part with internal cavities it needs to be cleaned to remove unmelted powder particles. The part also needs to be flow checked to make sure that internal cavities are clear. (Pat. US 20140140859 A1, 2014, p. 1-3.)

Effusion cooling is based on a thin film of cooling flow passing between the outer wall of a combustion chamber and an effusion cooling plate. This cools the components and allows them to work at better efficiencies. (Sun & Huang & Wu & Miao, 2009) Additive manufacturing can be used to construct internal cooling channels in effusion plates. The advantage of cooling channels made by additive manufacturing is that they can be manufactured with a curved cross-sectional geometry. They can provide cooling in gas turbine engine combustors and prevent thermal expansion and wear in the components. (Pat. US 20140202163 A1, 2014, p. 1-2.)

In hydraulic flap actuator, conventionally the fluid flows in bored channels inside the block. The bores are straight lines and are sealed toward the environment using plugs. Boring means that the part needs to be made relatively large which is undesirable in aerospace applications. With additive manufacturing the weight of the part can be reduced and the hydraulic
channels can be made without sharp-edged corners in the positions which cannot be reached with boring. (Pat. US 20140076154 A1, 2014, p. 1-3.)
6 DISCUSSION

This chapter presents the findings of this work. Also reliability of the work is evaluated and possible future research possibilities are discussed.

6.1 Reliability and objectivity
Due to rapid development in the field of laser processing only the most recent articles were used in the research part of this work. There is also a great number of articles that are made recently so reliability considering the age of the information is rather easy to keep high. Also most of the articles used are from scientific sources and are found through for example Elsevier or Science Direct which host a large amount of academic journals and can be considered reliable. Rest of the literature research is taken from patents and from websites of manufacturers. These sources are considered less reliable as they can be biased, especially the information in manufacturers websites can over praise the process they are trying to sell. When using these sources in the literature research part, the same things were tried to find in different, more scientific sources to validate the idea. The work is done objectively without much previous knowledge of the topic. With the same literature everyone can end up in the same conclusions presented in this work.

6.2 Key findings
Based on research done in this work, it seems that additive manufacturing processes are a valid way to produce internal features. Due to freedom of design, it is possible to make better and more effective constructs in parts where internal features are present. It is also possible to manufacture parts with equal structural properties to milled components of the same material. Laser additive manufacturing is still quite a new method for producing parts, compared to traditional milling; therefore it has time to evolve. Even if it does not replace traditional methods when making simple geometries due to its slow manufacturing speed, it can replace them when making complex internal features. Because optimisation of parameters in AM is crucial and the parameters are different to each material, the spectrum of material in use is quite narrow compared to traditional methods. Same materials like Ti64 and 316 steel kept appearing in different articles which also suggest this. More variety in materials can be expected as the time goes by and the process becomes more widely used.
The biggest downside of the process seems to be the manufacturing speed. The numbers used in this work are from a research quite old (2007) considering the age of the process. The speeds are probably improved by now but specific values could not be found which suggest that it is either a secret or done by the manufacturer companies to themselves. The speed can be improved by adding more laser power but it is limited by the growth of the melt pool which worsens the quality of the part. That is why there seems to be a upper limit to manufacturing speeds.

It seems that many people are trying to improve current designs of applications with cooling channels. Number of patents filed in the field of additive manufacturing and cooling channel additive manufacturing in recent years also suggests this. Most of the patents seem to concentrate in the field of aerospace technology, mainly in turbine components and their cooling. Due to environmental issues this is only natural direction to go as more efficient engines mean less environmental load and people are trying to profit from it.

6.3 Value of this research and comparison to previous research
This research was made based on existing literature. Due to that it does not include a lot of scientifically new information. Even if key findings part of this work may provide new perspective to the topic, the novelty value of this research is quite low. Making work on this topic more valuable is discussed in the future research chapter.

6.4 Future research
The future research based on the subject could include manufacturing test pieces with internal channels as some actual research could greatly benefit the industry. Surface quality improving and self-supporting channel shape design should be important research topics as well as improving the processing times without reducing the quality of the finished part too much. Also different materials and their properties and processing parameters should be researched as the material range used in the articles seemed quite limited.
REFERENCES


