3D PRINTING IN ROTATING MACHINERY

3D-TULOSTUS PYÖRIVISSÄ KONEISSA

Lappeenranta-Lahti University of Technology LUT

Bachelor's Program in Mechanical engineering, Bachelor's thesis

2022

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Examiner: D.Sc. Eerik Sikanen

ABSTRACT

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In this thesis I will examine based on existing literary studies the potential applications additive manufacturing ana their usefulness in rotating machinery.

3D printing can bring new possibilities to rotating machinery. With potential of new geometries and improved efficiency by implementing additive manufacturing. Due to rotating movement of components the weight and mechanical properties are highlighted. These advances can be achieved by incorporating new geometries such as lattice structures into components. Environmental benefits can be gained by switching from subtractive manufacturing to additive manufacturing.

Challenges with additive manufacturing are the surface roughness that is inherent to many of its processes as additional post processing is required to achieve the desired finished part. Commercial viability has limited much of current additive manufacturing applications into expensive and complex machinery such as turbines.

TIIVISTELMÄ

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3D tulostus pyörivissä koneissa

Konetekniikan kandityö
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Avainsanat: 3D-tulostus, Lisäävä valmistus, Pyörivät koneet.

Tässä opinnäytetyössä tutkin jo olemassa olevien kirjallisten tutkimusten pohjalta lisäävän valmistuksen mahdollisia sovelluksia ja niiden käyttökelpoisuutta pyörivissä koneissa.

3D-tulostus voi tuoda uusia mahdollisuuksia pyöriviin koneisiin. Lisäävä valmistus mahdollistaa uusia geometrioita ja paremman tehokkuuden. Komponenttien pyörivän liikkeen myötä paino ja mekaaniset ominaisuudet korostuvat. Nämä edistysaskeleet voidaan saavuttaa sisällyttämällä komponentteihin uusia geometrioita, kuten hilarakenteita. Myös ympäristöhyötyjä voidaan saavuttaa siirtymällä lisäävään valmistukseen.

Lisäävän valmistuksen haasteita ovat pinnankarheus, joka on usein perinteisiä valmistusmenetelmiä heikompi. Tämän vuoksi osat saattavat vaatia jatkoprosessointia. Kaupallinen kannattavuus on rajoittanut lisäävän valmistuksen käyttöä monimutkaisiin ja kalliisiin laiteisiin kuten turbiineihin.

SYMBOLS AND ABBREVIATIONS

AM = Additive manufacturing

SLM = Selective laser melting

NdFeB = Neodymium-Iron-Boron alloy

CFD = Computational fluid dynamics

AFM = Abrasive flow machining

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Abstract

Symbols and abbreviations

1 Introduction

3D-printing also known as additive manufacturing is a new and emerging form of manufacturing. It brings many possibilities to designers and engineers in numerous fields. In this thesis I will focus on its applications in rotating machinery through existing research and studies on the subject.

I have compiled research and studies on this subject to help better understand in which scenarios in is preferrable to utilize additive manufacturing in rotating machinery, as it brings potentially superior material qualities, lower cost of manufacturing or enables some new internal geometries within components that are beneficial to the function of the machine.

1.1 Background

3D printing also knows as additive manufacturing is a manufacturing process where material is conjoined layer by layer based on 3D data to create the desired shape. Common additive manufacturing techniques are laser-based processes and extrusion processes. In a laser process a medium to low power laser is sued to melt, solidify, or cure material. They can be further divided to two subcategories based on how they change the phase of the material. In laser melting the material is supplied as a powder to a powder bed or directly by a nozzle. Laser beam then melts the material and after it cools it solidifies into the desired shape. In laser polymerization the base material used is generally a photosensitive resin which is cured into shape by the UV radiation of a low power laser. Laser based methods are generally used for 3D printing metals and methods such as selective laser melting (SLM) are used in many examples of additive manufacturing found in this thesis. Simple diagram of SLM process in figure 1 (Bikas, Stavropoulos, Chryssolouris, 2015).

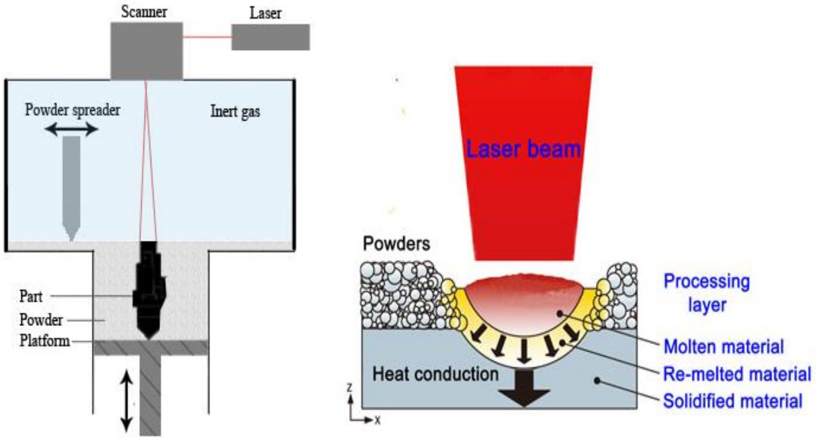

Figure 1. SLM process. (Materflow, 2021)

Extrusion processes use a heated extrusion nozzle to soften or melt material that is fed by a wire. The melted material is passed through the extrusion nozzle which places the material in the desired shape. Material is the allowed to cool, forming the part. Extrusion processes are usually used for plastics as they melt in much lower temperatures than metals. (Bikas et al., 2015).

In cold spray additive manufacturing high temperature gases are used to accelerate powder with high velocity which then impacts the substrate or component. It uses the kinetic energy of the powder particles rather than thermal energy to achieve deposition. Deposition is based on metallurgical bonding that is caused by local plastic deformation as the powder particles impact the substrate at high speed. Advantage is that the material stays as a solid through the entire process and thus avoids issues such as oxidation, residual thermal stress, and phase transformation. (Yin et al., 2018).

Electron beam additive manufacturing uses as the name implies an electron beam to melt the raw metal into a desired shape. The feedstock is either metal wire or powder. The process takes place under a vacuum which makes it very useful for materials that are highly susceptible to oxidization such as titanium. (Gong, Lydon, Cooper, Chou, 2014).

1.2 Research problem

Additive manufacturing is a broad and developing field of manufacturing with new methods and improvements to existing methods being developed all the time. A designer or an engineer who wishes to apply such methods to his or her design may not be aware of the latest developments due to the time that has passed from their education on the matter. Alternatively, the economics might have changed in the favor of additive manufacturing compared to traditional methods in recent time.

1.3 Goals

Goal for this thesis is to provide a look into applications and potential of additive manufacturing within rotating machines. Attempting to show in which types of scenarios of components additive manufacturing gives an advantage over more traditional methods, whether it’s through cost saving, manufacturing time or simply components with such geometries that could not be replicated with other methods. Potential problems with using AM are also presented. As the subject for this thesis is quite broad, I couldn’t go into that much detail on every application and use case for AM within rotating machinery. There are very many types of rotating machinery, and some are covered in this thesis much more detail than others.

2. Methods

This thesis is done as literary research on already existing material related to 3D-printing in rotating machinery. Results were gathered from various sources and analysis of results was done with the help of the SWOT method.

2.1 Research methods

Research of literary sources was mainly conducted through LUT Primo database. Various search terms were used such as 3D printing, additive manufacturing, turbine, compressor, pump, motor, rotating machinery, and various combinations of these terms. Google scholars was used when trying to find studies about specific parts or use cases. If a suitable source was found from Google scholar, I would take the name and find it in LUT Primo to make sure that it met the requirements I set. The results were limited the results to 2017 or newer as the field of additive manufacturing is developing rapidly and using old sources would give potentially misleading and incorrect information. The only exception was some sources used in the introduction to describe AM methods as the basic idea of these hasn’t changed even with more modern machinery and utilization. Additionally, I only used peer-reviewed sources to improve the reliability of the source material.

Validity and reliability of the research used in the thesis was ensured by using peer-reviewed studies from a reliable database, and by making sure that the research used was applicable to this thesis. More in-depth information on validity and reliability can be found in section 4.

All studies use in the thesis concerned rotating machinery. I did not include sources that simply studied the general implementation of AM. Research specific to rotating machines was used. Research comparing conventionally manufactured components compared to 3D printed ones were the primary target for my research. These present the new potential that is gained from AM and show what is required in terms of re-engineering and manufacturing.

2.2 Analysis methods

In this thesis analysis was conducted utilizing SWOT. This was done to discuss the potential strengths and weaknesses of additive manufacturing in applications that were studied. Additionally making comparisons between sources on the effectiveness of additive manufacturing in various machines. Though was given on why AM should or could be used in these applications. Potential problems that arise from AM are presented as well.

Statistic from the studies on the relative stresses, weight, and other factors such as carbon footprint over the lifecycle of the component are found in the results section. From numerical statistic it is easy to present and draw conclusions on the effectiveness and benefit gained from switching to AM. Observations made in the research on the material quality, surface finish and manufacturing process gave insight into the difficulties and challenges that are faced when applying a new manufacturing method into a product.

3 Results

Here are examples of AM in rotating machinery that are either experimentally proven or potentially in use commercially already. All information here is from existing literary sources on the subject. Focus is primarily on turbines, pumps, and motors as those are not only very common machinery, but they also have great potential to take advantage of AM. Other machinery is discussed in less detail.

3.1 Turbines

Improving the cooling of hot turbine components is key to improving efficiency and to enable higher power output. Bang et al. (2021) studied implementing hollow cylinder structures comprising of three perforated plates with two channels within components to aid cooling as seen in figure 2. Only additive manufacturing allows such complex internal geometries within components. (Bang et al., 2021).

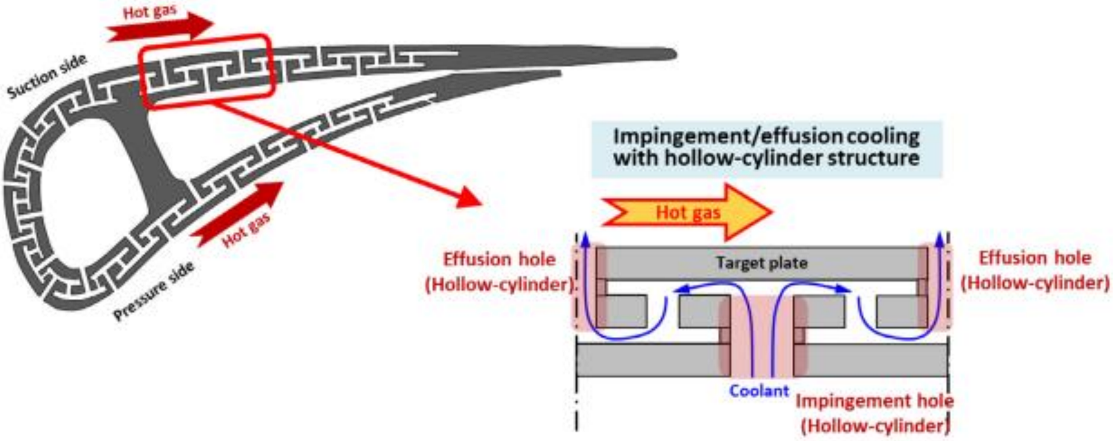

Figure 2. Cooling structure within the turbine blade. (Bang et al., 2021).

Turbine section of aircraft engines is a very hostile environment and components there may operate in temperatures up to 1650 ºC. Presence of corrosive and oxidative gases add further demands to components. Due to these factors the turbine blades demand specialized manufacturing methods. They are usually fabricated using investment casting and typically display one of the three common microstructures (equiaxed or polycrystalline, directionally solidified, and single crystal). Due to this complex processing turbine blades for aircraft engines are very expensive and a set of blades for and engine may take 60-90 weeks to produce. This long and costly production causes issues with defects and material damage from service as replacements are costly. Traditional manufacturing methods cannot repair the specific crystal structures required for these turbine blades. Therefore, additive manufacturing is being pursued for this purpose of repairing damaged turbine blades. (Nicole, Basak, 2020).

In figure 3 we can see methods that have been used to successfully repair single crystal turbine blades. This process is not without difficulty. Turbine blade geometries are highly complex due to the presence of various internal cooling channels. To repair such complex geometry very tight control of all process parameters is required. Additionally thin geometry features suffer from warpage due to residual buildup of stress during thermal cycling that is inherent in additive manufacturing techniques. These repaired surfaces are also and order of magnitude rougher than the original cast surface. (Nicole, Basak, 2020).

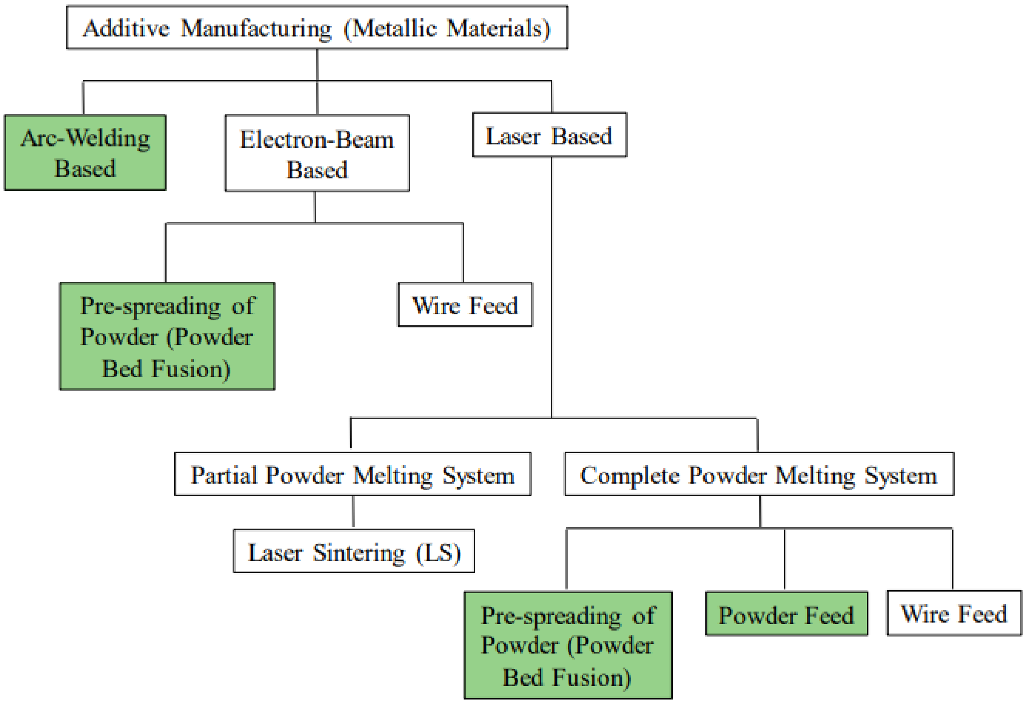

Figure 3. Green boxes show processes that have had success in repairing turbine blades (Nicole, Basak, 2020).

Material choice in turbine blade tip repair was studied by (Keshavarz et al., 2021) much like (Nicole, Basak, 2020) they too noted the major problems with repairing turbine blades made with single crystal material. In their study they focused on a new powder blend 4275M72 which consists of 75% nickel based R142 and 25% cobalt based M72 powders. They used Lase directed energy deposition (LDED) AM to repair the blade tip. They found that the new powder blend performed better compared to commonly used Rene 142 and Rene 80 powder blends. The new 4275M72 powder blend had superior mechanical properties and oxidation resistance and waws deemed suitable for tip repair of turbine blades. (Keshavarz et al., 2021).

In addition to repair the manufacturing of turbine blades they themselves can be made with AM. Major companies such as Siemens and General Electric are pursuing this. In figure 4 a miniaturized version of siemens SGT6-8000H gas turbine made with AM. It only has 68 parts. (Vialva Tia, 2019)

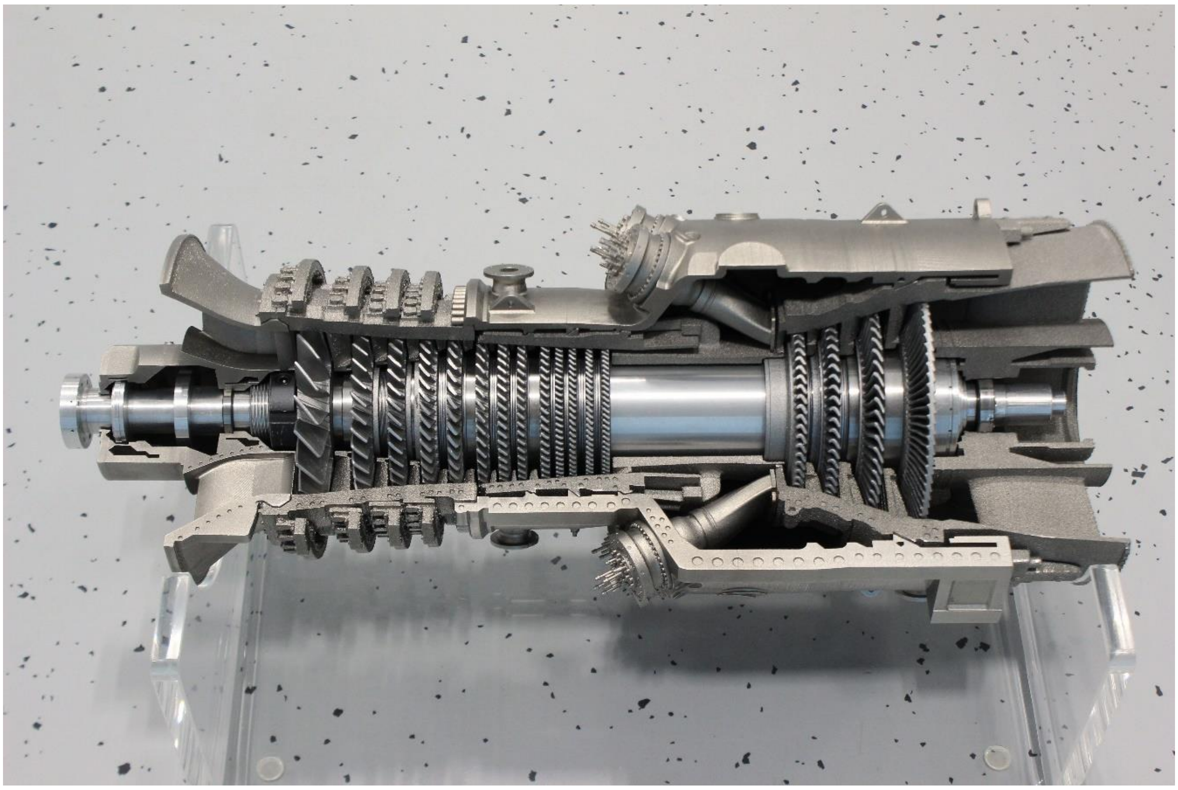

Figure 4. 3D printed miniaturized version of Siemens SGT6-8000H made by Fraunhofer IFAM and H+E-Produktentwicklung. (Vialva Tia, 2019)

To combine the benefit of both AM and traditional methods (Rittinghaus et al., 2020) tried hybrid manufacturing techniques by combining direct energy deposition (DED) with traditional methods such as casting or with another AM method in laser powder bed fusion (LPBF). Difficulties were the differing chemical composition and microstructure between the materials made with different methods. Testing the mechanical properties of test samples that utilized multiple methods was good in comparison to control samples. This shows promise for combining multiple manufacturing methods in a single component. It also shows the potential for DED to be used to repair cast turbine blades. (Rittinghaus et al., 2020).

AM can be used to repair components such as gas turbine burners and bring potential environmental benefits. This was studied by (Walachowicz et al., 2017) Gas turbine burner is the component that mixes hot compressed air and the fuel. The burner is a critical part for reliable operation of gas turbines. Due to high operating temperatures burners need to be regularly exchanged. The burner is brought back to the manufacturing facility to be refurbished and to replace the damaged tip section. (Walachowicz et al., 2017).

(Walachowicz et al., 2017) Looked into the repair process of a burner from a Siemens industrial turbine, example seen in figure 5, using laser beam melting (LBM). They focused on the reduction of material footprint, primary energy consumption and carbon footprint using AM process for the repair instead of a conventional process. With AM only the damaged part had to be removed from the burner tip thus reducing waste. After removing the damaged section, the burner is placed in a specialized laser beam melting (LBM) machine in a precise alignment. The tip is then rebuilt by the machine. In the study (Walachowicz et al., 2017) found that using an AM process for the repair utilized 89% of the material within the process compared to 21% percent for conventionally repaired burner. This shows a much lower amount of waste material from the process. Although much of this excess material can be recycled. AM process becomes much more efficient when looking at the total carbon footprint. Conventional machining has a much lower material utilization and thus requires much more starting material to produce the same part. Recycling all this excess takes time and energy increasing the carbon footprint for the process. Using less starting material with AM makes the entire process much more efficient. (Walachowicz et al., 2017).

Figure 5. 3D printed gas turbine burner from siemens. (Siemens, 2018)

Demand for clean, efficient, and durable sources of electricity has created an opening for micro power turbines as a source of power for locations where renewables are not an option. Issue with small scale gas turbines is that they are much less efficient compared to larger ones. To solve this (Adamou et al., 2021) applied AM to create a more efficient micro gas turbine with lower emissions. Notable potential application for these are small combined heat and power (CHP) systems for building and unmanned aerial vehicles. Small gas turbines are already used in ground transport applications. (Adamou et al., 2021).

This new micro gas turbine made extensive use of additive manufacturing. Many different types of swirlers were tested including one made with traditional methods to gain points of comparison, swirlers made with AM can be seen in figure 6. Fuel injectors were specially designed to suit AM with a teardrop design. Size of the teardrop was limited the smallest possible that didn't require post-processing due to the surface roughness inherent in AM methods. To improve the mixing of air and fuel a mixer with a lattice structure was implemented into the injectors. Creating a complex structure within the injectors also highlighted the unique possibilities of AM. To extent the service life a specialized cooled liner was designed utilizing AM. (Adamou et al., 2021)

Figure 6. Swirlers used in the study after printing. (Adamou et al., 2021)

Testing was done using computational fluid dynamics (CFD) and a prototype combustor made with the forementioned experimental parts utilizing AM. Data from the prototype was used to validate the CFD model. Testing showed the superiority of the AM designs. operating temperatures were much lower, pressure losses were reduced by 174 to 88 kPa, Nitrogen oxide emissions were reduced by 49-75% and carbon monoxide concentrations 22-40%. The lattice structure within the injectors improved fuel mixing by 20%.

3.2 Pumps

In a centrifugal pump for mechanical pump fluid loops the efficiency relies primarily on design and the performance of the closed impeller. The performance of the closed impeller is related to the manufacturing process in terms of dimensional accuracy and quality of the surface. The closed impeller is a low volume item that has a very complex geometry and for this they are a prime use case for additive manufacturing. Closed impeller has a shroud on both sides of the vanes. Example of a closed impeller can be seen in figure 7.

Figure 7. Closed impeller (RMC, 2018)

(Adiaconitei et al., 2021) researched the potential of additive manufacturing for closed impellers in mechanically pumped fluid loop (MPFL) systems in space applications. Multiple building orientations were used to fabricate three impellers. Selective laser melting was the AM method used in this study. To find the optimal building orientation dimensional accuracy and surface quality were closely monitored. To further improve surface roughness further abrasive flow machining (AFM) was utilized and showed promise.

(Ponticelli et al., 2021) Studied creating an impeller for a submersible electric pump. They also used selective laser melting (SLM) in their study. They sought to reproduce an impeller that is already designed and manufactured by traditional means and re-engineering it to suit additive manufacturing. The impeller re-designed for and made with AM was 1.5 times heavier than the original. This was mainly due to the total material volume increasing from 4108 mm^3 to 6162 mm^3 caused by chances to thickness of certain parts. This increase weight was not perceived as a major issue as the new impeller was far more robust and allowed operation at higher velocities with the same stress levels. Not all sections were thickened. The blades were thinner than before and combined with simplification of geometry by removing overhangs reserved for bending and welding, resulted in an increase volume available to increase the flow rate. Surface roughness was found to be quite high as with study by (Adiaconitei et al., 2021) (Ponticelli et al., 2021).

One of the issues found in the studies was that with AM processes is deposition of support material in closes areas where it cannot be easily removed after the manufacturing. To alleviate this issue three building directions were investigated, 0-, 32- and 45 degrees of angle from the base as seen in figure 8. Surface roughness was another issue, but this is known for AM so (Adiaconitei et al., 2021) utilized abrasive flow machining (AFM) to improve the surface in interior areas of the 3D printed closed impeller. This research was a great step in proving the application of AM to impellers. (Adiaconitei et al., 2021; Ponticelli et al., 2021).

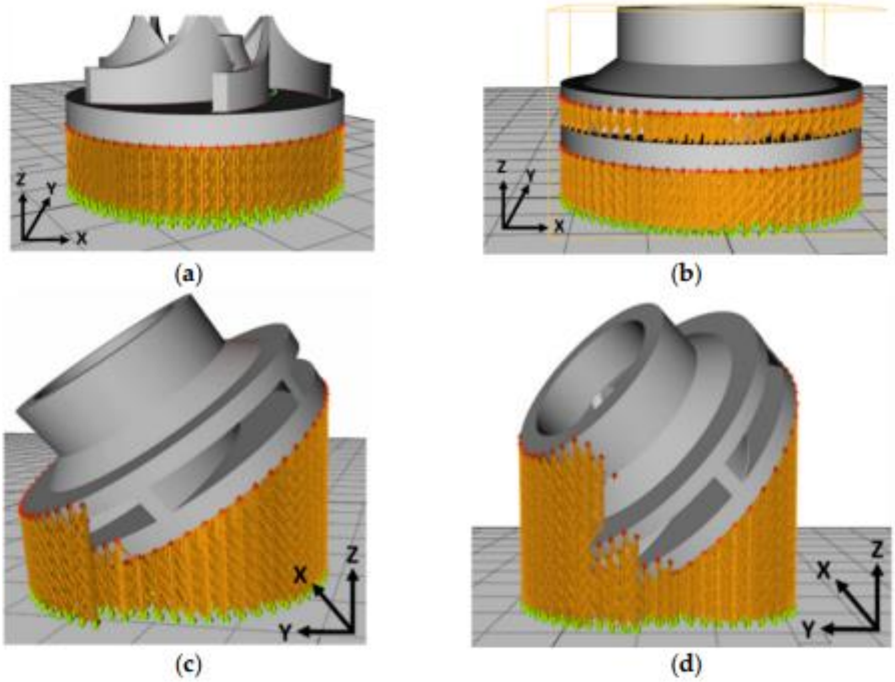

Figure 8. CAD models showing orientation and support structure of impellers. (Adiaconitei et al., 2021)

3.3 Motors

The automotive sector is moving towards electrification. This is driving demand for electric motors. Electric motors are also widely used in industry. Permanent magnet motors are the most popular for electric vehicles as they provide great efficiency and power density. Issue is their high cost, up to 50% of which comes from the magnets. Magnets require rare-earth metals, and their fabrication takes numerous assembly steps and is labor intensive. Because of this the magnets are mostly made in very simple shapes which limits the design of the motor itself. (Lamarre, Bernier, 2019).

Application of cold spray additive manufacturing to permanent magnets was investigated as a mean to simplify production and enable more complex shapes for magnets. In cold spray additive manufacturing fine powder particles are accelerated in a high-speed stream of compressed gas. When they impact the substrate of backing plate they deform and bond together to form a layer of solid material. In the study it was found that magnetic properties remain during the spray process. Key part of the study was to find the correct parameters for the process to achieve high magnetic performance from the finished part. The magnets were made from a NdFeB-Al composite which consist of neodymium-iron-boron alloy and aluminum. For the cold spray process, the gas pressure was 4.9 MPa and temperature was set at 600 ^{o} C. (Lamarre, Bernier, 2019).

The magnetic properties of cold sprayed magnets were not as good when compared to industry standard magnets. This was contributed to the requirement by the cold spray process for a binder material which limits the amount of magnetic material per unit of volume. On the other hand, the mechanical properties were excellent. Ultimate tensile strength for cold-sprayed magnets was 200 MPa which is far above the industry standard for other fabrication methods. These mechanical properties come from the use of a metallic binder and the high inter-particle cohesion that is achieved from cold spray additive manufacturing. Cold sprayed magnets could be very useful in application in which high strength is required. (Lamarre, Bernier, 2019).

Using additive manufacturing enables much more complex shapes to be made. Complex shapes can enable higher performance by utilizing 3D magnetic fluxes. This can be done by increasing magnetic interaction within the same volume, for example by creating an hourglass shape as seen in figure 9. Potential issue with these different shapes is magnetizing them, as magnetization equipment would have to be customized to these new geometries to achieve the correct magnetic field. (Lamarre, Bernier, 2019).

Figure 9. Rotor part for an electric motor made from NdFeB-Al composite and pure iron. (Lamarre, Bernier, 2019)

3.4 General applications

Topology optimization is a process in which structure is designed for maximum stiffness and reduced weight. Combining this with additive manufacturing and lattice structures can be used to develop some incredibly complex, lightweight, and durable designs. (Boccini et al., 2019) Sought to implement this trio of design features into rotating machinery.

Lattice structures are topologically ordered, 3-dimensional with usually a repeating pattern of cells. Examples can be seen in figure 10. Thanks to this structure components made with them can possess exceptional mechanical properties far above what the base material alone could do. Additive manufacturing is the best way to manufacture lattice structures as creating complex and repeating 3D cells within material is almost impossible otherwise. (Maconachie et al., 2019)

Figure 10. Cubes made with AM showcasing lattice structures. (Gen3D, 2021)

(Boccini et al., 2019) Wished to create a process of optimization for rotating machinery in which an existing part was taken and improved with topology optimization and lattice structural optimization. To expand the potential design space for the lattice structures additive manufacturing was used as manufacturing layer by layer removes restrictions on internal geometry of parts. In figure 11 the idea of the optimization procedure is shown. (Boccini et al., 2019).

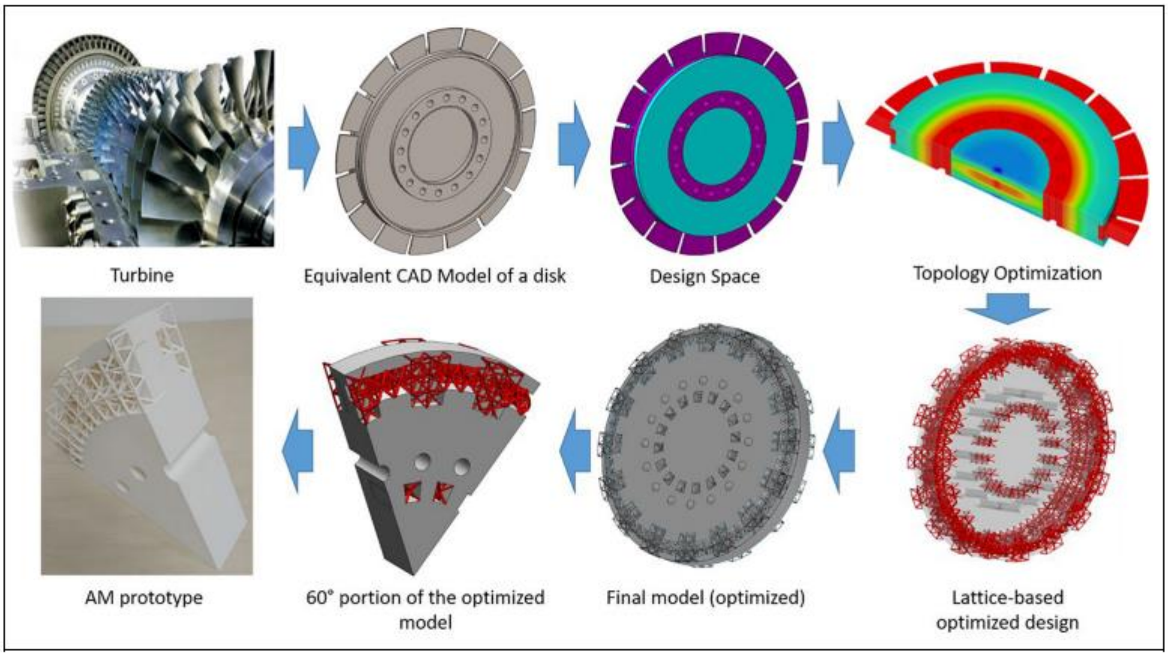

Figure 11. The procedure proposed by (Boccini et al., 2019)

As a test case (Boccini et al., 2019) applied his procedure to a turbine disk. He compared the new disk with lattice structures to against the original. Metrics studied were mass, stresses within the disk, and in terms of safety margin and safety range in vibration frequency. Results can be seen in Table 1. As we can see from the results optimization worked in all measured metrics. In theory this process could be utilized for any rotating component in turbomachinery, but further studies are required to validify the results in other components. (Boccini et al., 2019).

Table 1. Results of optimization for turbine disk by (Boccini et al., 2019)

	Standard disk	Optimized disk	Improvement (%)
Mass (kg)	200	166	17
Safety margin (Hz)	120	199	66
Safe range (Hz)	429	446	4
Maximum stress (MPa)	788	739	6

Environmental effect of AM versus traditional methods was studied by (Torres-Carrillo et al., 2020) with a life cycle assessment (LSA). In this study an aeronautical turbine blade was used as a test subject. Studied metrics were global warming potential (GWP), Acidification Potential (AP), Ozone layer Depletion Potential (ODP), Human Toxicity Potential (HTP), and Human Toxicity (HT). Test size was a batch of 600 turbine blades. Results can be seen in table 2. As you can see AM reduces all emission types monitored in the study. This shows the potential of replacing conventional methods with AM as one way for manufacturing companies to improve their environmental record. One potential issue was highlighted in the study. If the components made with AM require post processing due to surface roughness this would reduce the environmental advantage. Analysis was done on the potential effect by using different scenarios with varying degrees of post processing. In the scenarios tested AM still had lower carbon footprint, but further study is required to fully calculate the effect of post processing on the life cycle carbon footprint. (Torres-Carrillo et al., 2020).

Table 2. Results from (Torres-Carrillo et al., 2020).

Indicators	GWP	AP	ODP	HTP	HT cancer	HT non-cancer
Unit (kg-eq.)	CO_2	SO_2	R11	DCB	CTU_h	CTU_h
Conventional manufacturing	7325.28	20.55	3.16E-07	323.15	5.80E-06	2.35E-05
Additive manufacturing	7027.20	19.39	2.96E-07	305.68	5.46E-06	1.94E-05
Emission reduction (%)	4	6	7	5	6	17

CO2: Carbon dioxide; SO2: Sulphur dioxide; R11: Trichlorofluoromethane; DCB: Dichlorobenzene. CTU_h: Comparative toxic unit for human toxicity impacts.

4 Analysis

Here I will analyze the potential of AM in rotating machinery based on research and other material presented in the results section. I will also discuss the validity and reliability of the data used in this study and present subjects from this thesis that require further study in order to judge their usability.

4.1 Reliability and validity

Reliability of the information presented should be good given that I only utilized peer-reviewed sources from the LUT primo database. Only things in which I used non peer reviewed sources was for some of the images used to better illustrate the subject being presented. This was mainly because finding suitable images from the research papers alone was somewhat difficult, but any images that contain relevant information or are presented as sources of information rather than just illustrations are sourced from the research papers. I restricted my search to new results as when dealing with a field such as additive manufacturing that is developing so quickly using old sources could present information that is not relevant anymore.

Validity of this study was maintained by focusing on the research of AM methods specifically in rotating machinery and avoiding studies that use AM in other kinds of applications. Only exception was the sources used to describe various AM processes in the introduction as the basic idea of the various processes doesn’t change even if they are utilized in a different way.

4.2 Key findings

Strengths of additive manufacturing are its adaptability to new designs. It is most useful in applications with complicated components with low production numbers. As with AM complex parts can potentially be made as a single unit instead of comprising from multiple parts as seen in a redesigned close impeller by (Ponticelli et al., 2021), and the superior economics of conventional manufacturing in large scale production can’t be utilized. In rotating machinery turbines have seen a large amount of research when it comes to AM utilization. This is most likely due to the high stresses and temperatures and complexity of the parts within turbines. In turbines an increase in performance that is gained by using a more expensive part is most likely worth. Turbines are expensive to begin with and the performance metrics are a priority in most of their use cases. This contrasts with pumps and electric motors in which AM can bring performance increases but whether it’s worth it remains in question. Most current commercial applications of AM in rotating machinery are found in turbines.

The ability for AM to create the metallurgical structure similar within the base metal opens a lot of opportunities to use the method to repair damaged components. As seen in the turbine section AM has been studied extensively for turbine blade repair. Thanks to the ability to fill in complex shapes is key as depending on the application of the component the damage may not be uniform. By selecting the correct AM method and process parameters many kinds of damaged components could be brought back to use, saving money and the environment by reducing demand for newly manufactured parts.

Potential for reducing the carbon footprint with AM is great. Switching from conventional manufacturing to additive can reduce emissions as seen in the study by (Torres-Carrillo et al., 2020). In addition to reduction from the manufacturing process AM can enable more efficient designs. This can be seen as a reduction in fuel or energy consumption, or cleaner and more efficient burning in the case for gas turbines.

Combining AM with other advances in material and structural engineering can lead to revolutionary designs. Work by (Boccini et al., 2019) in creating a method of integrating topology- and lattice optimization into turbomachinery components is a great example of this. Lattice structures could become commonplace in many components thanks to their mechanical and weight characteristics. This would greatly expand the market for AM.

The quality of the surface finish with 3D printed parts is something to take into consideration. As surface roughness was noted as an issue in many of the studies preciously covered. This can be addressed with post processing of the part with methods such as abrasive flow machining. In this process abrasive fluid is flowed through the rough area to grind it to a desired smoothness. The process is used especially if the part contains internal cavities or small complex structures and with AM these kinds of design features are common.

4.3 Further study

Many of the examples of AM found in the results section are from initial studies in which components were created with additive manufacturing and compered to conventionally manufactured ones. Much of the studies used simulations to gain data and stated that long-term real-world studies would be needed to verify results.

Commercial viability of many of these use cases also needs further study. Almost any component that can be made with conventional methods can be made with AM. This does not mean that AM is suitable manufacturing process for every case. If the costs or production time would be increased and the component doesn’t require some elaborate geometry AM is not worth it. To properly assess commercial viability, an in-depth study into the cost of the numerous AM methods compared to the long list of conventional methods is required.

5 Summary

3D printing is quickly gaining ground in rotating machinery with great interest in utilizing it to many components. The ability to create complex geometries without numerous sub-assemblies or extensive machining it can open new possibilities. Commercial application is already taking place with turbines in aerospace and power generation for example. AM can be used to repair broken components with its ability to form complex shapes with the correct microstructure on the damaged section of a part.

Additive manufacturing has the potential to bring a new generation of more efficient and reliable machinery. If engineers learn to utilize AM in situation where it brings the most benefit great strides can be taken to create revolutionary designs. With the world becoming evermore concerned with climate change AM can be a powerful tool in building rotating machinery with a lower carbon footprint.

Additive manufacturing opens the potential for new developments in material engineering to be applied to components. Lattice structures are one such example. Turbomachinery has some of the highest potential to take advantage of these developments. Reducing mass in rotating parts greatly reduces the stress levels and improves longevity of machinery. It will take some time for all these advancements to find their way into market products. Currently aerospace industry is leading the way for AM adoption.

I learned a lot about 3D printing and its applicability to rotating machinery whilst writing this thesis. I believe AM will open a wide range of new solutions to current limitations in machinery and be a great tool for engineers and designers going forward. If I end up working in industry with the machinery, I studied for this thesis I will have plenty of ides for product improvement.

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