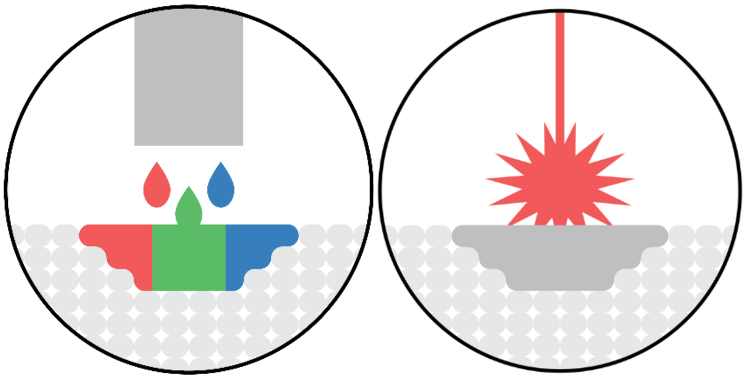

2021

Additive manufacturing

The technology of the future

Design considerations for additive manufacturing in industry

I am an employee in an engineering firm that has been tasked in analyzing design considerations two different product that are going to be made with the use of the additive manufacturing technologies Material Jetting and Powder Bed Fusion, and compare to said technologies with the traditional manufacturing method of producing the two products.

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Abstract

I am an employee in an engineering firm that has been tasked in analyzing design considerations two different product that are going to be made with the use of the additive manufacturing technologies Material Jetting and Powder Bed Fusion, and compare to said technologies with the traditional manufacturing method of producing the two products.

The product that was being manufactured for Material Jetting technologies was a medical grade brain model, which requires being durable, color coded, and accurate. It was discovered that the technology is extremely good in terms of its accuracy, the natural printed surface finish, and the speed of manufacturing in terms of both printing speed and lead times. However it is nonetheless limited by the capital price, although the technology's strengths do outweighs that of its drawbacks when compared to the traditional manufacturing way of making brain models which is molding.

In terms of the design considerations, it was found that the technology will help us color code the product and make internal features with relative ease. When compared to the average size of a human's brain, the manufacturer will be able to produce 20 models during one print cycle, with the best material to potentially be used being standard resin, polypropylene simulating resin. It has also been found the most suitable print orientation to be used for the product is to have printed upside down. Lastly, in terms of finishing, due to the already really good surface quality that material jetting provides, it was found that the as printed finishing would be suitable although if needed acetone vapor smoothing could be utilized.

The second part of the assignment was the consideration of Powder Bed Fusion technologies for the manufacturing of watch cases, which is a product that requires good dimensional accuracy, durability, and most importantly aesthetic appeal. The three different Powder metal printing machines were compared, with them being DMLS, SLM, and EBM. It was eventually decided that SLM printing was most suitable for the product due to it having a smaller porosity percentage to that of DMLS printing, and it was found that it was better than EBM printing in both surface quality and accuracy. It was also found to be better than CNC machining due to the capital expenses being less than that of 5 axis CNC machines, SLM printing also produce less waste, and are also relatively more accurate, which outweighs the disadvantages of them being slower and having a worse as print surface finish.

Lastly, in terms of design considerations it was found that the printing technology would help the manufacturer in printing more detailed cases as well as allow them to create both the bezel of the watch and the case at the same time. It was also discovered that 105 watches are able to be printed in once cycle, product orientation is best left standing upwards, next to that, it was decided that a type of ceramic should be taken into consideration for the product. Finally, for the finishing technique it was determined that out of polishing, blasting, and brushing, polishing would be the most suitable one for the product.

CAD modeling was also considered and it was found that 3D scanning is expensive but it most preferable for products that have been made, while traditional software modeling being the method that has to be utilized for products that have yet to be created in real life.

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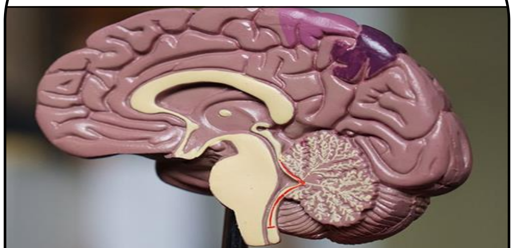
Material jetting

Product 1 – surgical brain models



Surgical brain models are highly detailed plastic models that are used – according to (Kim, 2021) – to plan and simulate a brain surgery, either as practice for an incoming brain surgery or as training for medical students and surgeons. As well as to be able to visually explain a surgery's procedures to the patient, and as such, each model has to be tailored to the patient's brain dimensions. This is the product that is suggested for manufacturing using material jetting.

Product requirements

Dimensional accuracy:
Due to the product potentially being used as training or practice for a real incoming surgery, it is deemed of extreme importance and to be able to simulate the real experience for optimal performance and preparation, the model being as dimensionally accurate as possible to the real dimensions of the patient's brain

Clear surface finish:
A smooth and clearly visible surface is essential for the product so that the user is able to differentiate between one section of the model to another, such as outlining the arteries, and showing the frontal and temporal lobes with the use of different colors. As well as having as having a more detailed model for surgeons, this would as well make it easier to demonstrate the procedure to the patient.

Durability:
Due to the nature of surgical practice, the model is likely to be used multiple times, and as such it should be able to withstand wear and damage so that it won't fail in demonstrating a realistic brain surgery operation during a practice or training session with the model.

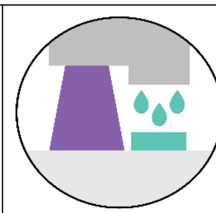
What are material jetting technologies?

Material jetting is an additive manufacturing process that utilizes photopolymerization and is initiated by installing a digital 3D CAD model into the material jetting printer. After the mentioned CAD model has been installed, the main operation of the printer starts with heating the material to 30-60 degrees Celsius as stated by (Gregurić, 2019). After which a platform, that is connected to generally two or more material containers to allow for multi-material printing and to also allow the use of dissolvable supports, said platform moves over a building bed, which then drops photopolymer resin as it is moving from one end of the printer to other, and therefore dropping the resin onto the build platform that is under it, nigh on immediately after the material has been dropped, a high intensity UV light that is located next to the nozzle is directed onto the material, which traces the geometrical shape of the product and due to the special properties of photopolymer materials when they are in contact with UV light, the polymer chains within the material are linked, which consequently then hardens the material, creating a layer of the product. After this the bed is then lowered one layer's height and the coating platform starts moving towards the other direction to repeat the process until every layer of the product has been made. An additional note to make is that this process does require support material for any overhangs within the product with an angle of over 45 degrees.

Types of material jetting technologies:

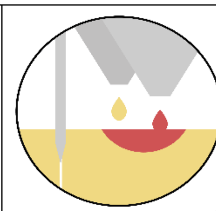
PolyJet

According to (Redwood, 2021), Polyjet printing material jetting printing is a process in which the platform drops the photopolymer material in a continuous fashion with the use of hundreds of small nozzles, in the process coating the build plate with the material which and simultaneously placing support material.



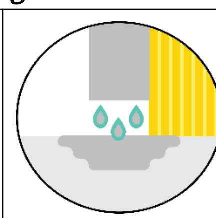
Drop on Demand

As stated by (Redwood, 2021), Drop on Demand printing (DOD) is similar to PolyJet in that it drops photopolymer resin onto a bed and cures it using UV light, however, DOD printing – just like FDM – doesn't cover the entirety of the bed but rather only drops resin in the location where it is going to be cured, with one nozzle being used for the material while the other for either an alternative material or dissolvable supports.

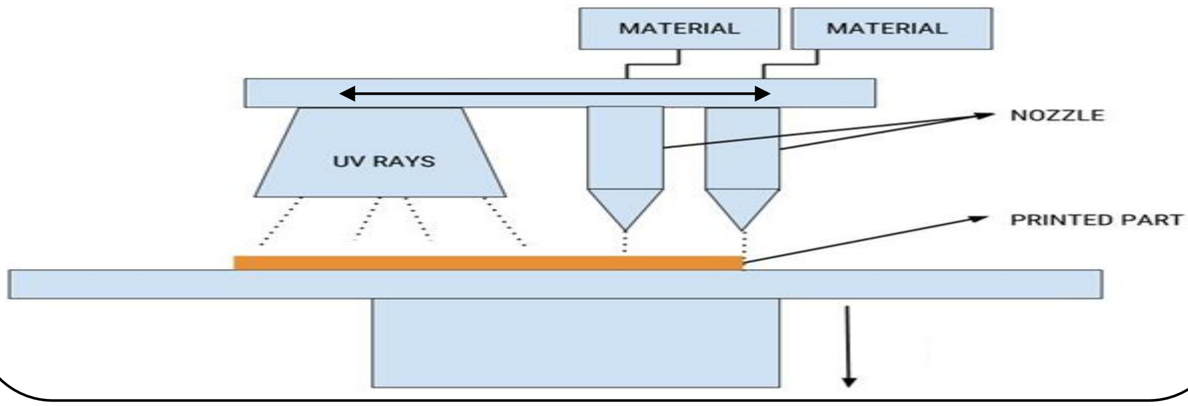


Nano particle jetting

As claimed by (Redwood, 2021), In contrast to PolyJet and DOD printing, Nano particle jetting (NPJ), it doesn't utilize photopolymerization, but is rather used for metals and ceramic, and as such, it isn't relevant it is a relatively new technology that has first been revealed in the May of 2016. The way it works is that liquid submerged nanoparticles of the material are placed on the bed as a layer and then are.. sintered to fuse the layer and evaporate said liquid.



Diagram



Main Characteristics of the technology

Multi-Material Production

Due to the fact that material jetting is capable using multiple material cartridges at once, this allows for the production of resin product that have multiple material simultaneously, rather than having to print certain section of the print with the required material and certain sections with the other – as one would have to do when using SLA printing – and as such, this opens many new possibilities when it comes to printing using the technology, such as the production of multi-colored prints that would result in a more accurate visual demonstration of products similarly to models and any products alike. Other than that, the ability to use multiple materials at once makes the use of dissolvable support material available by utilizing the second cartridge for a special type of material would be used specifically for support structure and would dissolve under certain circumstances, which would result in less damage being caused to the surface finish of the product during the process of removing the support structures.

Material Degradation

Caused by the special properties of photopolymer materials when are under UV radiation, they unfortunately degrade when they get in contact with them, and due to the main material being utilized in material jetting being photopolymer resins, this means that products created using the technology would not be able to last very long if its application revolves around it being placed outdoors or under a form of UV light, and would require further post-processing to prevent said issue.

Environmental Compatibility

Due to the main material that the technology makes use of being photopolymer resins, which are deemed a thermoset plastics, this brings up a major issue when it comes to material jetting's sustainability, especially in terms of recyclability, that is mainly due to thermoset polymers – unlike thermoplastics – not being able to be melted and reformed, but rather when an attempt at heating them is made, the polymer burns in lieu of melting, and as such they are considered unrecyclable.

Accuracy & Tolerance

When it comes to Material Jetting's tolerance, it is certainly one of the more notable ones that are currently out in the market, according to (Varotsis, 2021) that is due to it being only ±0.02mm, and also having a considerably low risk of warping and shrinking, which extremely important as this as this opens many opportunities to material jetting when it comes to manufacturing extremely intricate and detailed parts.

Set-up Expenditures

One of the major drawbacks to Material Jetting is the capital expenses required for the technology as according to (3D Source, 2021), the starting price of the machine is around 6,000 USD with the major MJ machines being around 75,000 USD. This causes multiple issues from the main one being companies potentially not wanting to invest in a technology that expensive and also not being viable for products of limited and minimal quantity.

Surface Properties

A really important point about material jetting is its different surface texture setting, as has been claimed by (Varotsis, 2021), there are two separate surface finish settings when working with material jetting machines, the first being a glossy finish with the other being a matte aesthetical appearance. The difference between the two different settings is that when the machine is operating on the glossy setting, it would only add support structures where it is deemed to be necessary, aforementioned location would be overhangs that are over 45 degrees or bridges. In contrast, for the matte finish, support structures would be added throughout the entirety of the print, which is due to the addition of support material being the main factor in giving the surface of the print a matte aesthetic finish. As well as that, because of the surface quality of a product that utilizes additive manufacturing technologies being directly related to the printer's accuracy since having better tolerances leads to a more even layer deposition, and due to the fact that material jetting has a notably good tolerance, it therefore leads to it having an extremely smooth and even surface texture, another point that contributes to this is – as stated by (Varotsis, 2021) – 16 to 32 microns layer thickness. However, if a print were to be done with the use of the matte print setting, the surface quality would be less smoother than that of the glossy finish, however, it would result in a more accurate product.

Speed of Production

As mentioned by (Gregurić, 2019), material jetting isone of the fastest AM technologies, and that is due to material jetting machines employing multiple nozzle, whether that being hundreds when talking about PolyJet printing technology or two if you're talking about DOD printing, it is still more than what other AM processes might be making use of, and as such, this allows for quick deposition of the material, and due to the curing step of the material not being a long process, these two points lead to a rather quick layer placing and hardening, which attributes to a fast speed in production, however, when compared to other manufacturing processes such as CNC or injection molding it is rather slow.

Build Capacity

As claimed by (AMFG, 2018), larger sized material jetting machines are around 1000x800x500mm in size, which is relatively on the larger side when compared to other manufacturing processes. This would allow for the manufacturer to be able to print multiple quantities of the product at once, leading to an even faster production rate.

Product justification

Strengths of material jetting

The most evident with material jetting technologies that the product would certainly benefit from is the fact that it is an additive manufacturing process, which allows the machine to bypass many **complexity issues** that the traditional manufacturing method for the product – which is molding – would not be able to, and would force the product to be made in separate pieces for it to later on be assembles. In terms of the brain model, inner segments of the brain or intricate parts might be of extreme difficulty to implement if traditional molding were to be used since as just mentioned they would have to be made separately and then joined which would be both time consuming and costly, however, due to material jetting's ability to overcome these issues with ease, said problems should not be something that the manufacturer should worry about when using the technology. Another really important point is the ability to **utilize multiple materials** at once, this is also major because as mentioned earlier, an outlining of the different section of the brain with the use of different colors would is one of the main requirements for the product, and the use of multiple materials at once would allow the manufacturer to make the entire product; with all of the required section and different colors in one process, unlike molding, which would require for the different sections that need to be in certain colors to be made separately and then joined together, or would have to be painted during post-processing. Also, due to the surface finish of material jetting technologies being extremely good, this would also help with the aforementioned point by allowing for a clear and smoother look, that if the product were to be molded, would require an extreme amount of finishing processes to be done to get as good of a surface finish. Also, **shrinkage and warping** does occur within Material jetting prints, however, the magnitude of said deformation is relatively little, especially when compared to that of molded products. As well as that, due to material jetting being an additive manufacturing process, **very little waste** would be generated since the only waste being made is from small bits that might be caused when finishing the product as well as support materials which can be fully negated if dissolvable supports were too be used.

A further advantages of material jetting that help with the required specifications of the product is the technology's extreme accuracy, as this would allow for more realistic training relative to the actual operation. The speed of production and capacity of the machine are certainly strengths that the machine possesses, however in terms of the product they aren't major, that is the case since the product is being tailored made, meaning that only a small batch – maybe even one only – would be made, and as such neither **volume of manufacturing or capacity** would be important. Another major strength of Material Jetting technologies over traditional molding is the **preparation time required** , which is an important point due to it being extremely helpful for initial setup and also redesign considerations are simple since a small prototype of the newer design can be made with the use of material jetting quickly and if the design were to be used as the final product the only procedure that would be required to do said change would only be the change of the digital CAD model. However, if the same redesign were to be done with molding as the main manufacturing process, the procedure would require the entire mold to be changed, which both a time consuming and a costly process, with no easy access to a test prototype.

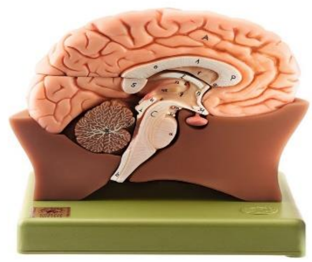
Limitations of Material Jetting

As mentioned previously, the product requires good durability, and since photopolymer resin **degrades** when it is in contact with UV light, and as such, care to make sure that it is not placed within contact of sun rays or medical appliances that might emit UV light should be taken, which isn't an issue that other manufacturing technologies such as molding would have to worry about since the freedom in **material selection** is much wider. The major drawback to using material jetting technologies for the product however, are the **capital expenditures** and the cost of running machine in terms of the material, that is the case because as mentioned earlier, the starting price of the technology is around 6,000 USD and can get much higher for better quality material jetting machines. In addition, as stated by (Gregurić, 2019), the materials used for the printing process are **expensive** as well, which would patently lead to more expensive prints. Another problem with Material jetting is the fact that the **CAD model would have to be optimized** to fit the additive manufacturing process, such creating a model that combines all parts that would traditionally be made separately, which could be a time consuming process.

Although the mentioned drawbacks to material jetting technologies are evident, they are minor as well, and that is due to the degrading process of the material being slow, as well as easily preventable by simply keeping the product away from a UV source. The cost of the machinery is certainly expensive, if said price was an issue, the build capacity could sacrificed since it isn't an important aspect for the product, which would lead to a huge decrease in the cost of the machine. Lastly, although the material cost is expensive, as mentioned earlier, print product would be slow, and as such not much material would be needed other than the one for the small required batch of the print. Nonetheless, the price of producing a mold for the product would be way cheaper than purchasing the machine, however, since the material cost would be less than the cost of producing a mold, and as such it would be less expensive to maintain the material jetting process compared to creating molds in the long run.

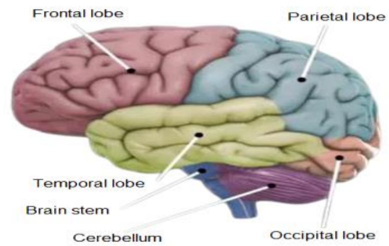
Design considerations

Internal features



A big feature that is generally extremely hard to implement and as such is missing from many brain models for said models to not only show the outer shell of the brain, but as well that be able to shows inner segments. The issue that deems this feature to be difficult to apply is that it would require for the inner parts of the model to be manufactured separately from the outer parts and for them to be later on joined, however due to material jetting being an additive manufacturing technology the entirety of the product – including the inner segments of the model – can be made throughout one cycle, which would not only decrease the price of manufacturing the product, but it would also allow it stand out more compared to other competitors on the market.

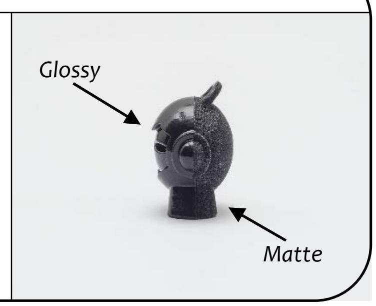
Color code



The main for function of a brain model is for the consumer to be able to tell apart from one section of the brain to another easily, and with respect to that, each segment of the brain is required to be color coded to be able to highlight them more clearly for the user. As such, the frontal, parietal, temporal, and the occipital lobes, as well as the cerebellum and the brain stem with the addition of any inner parts of the brain should all printed with the use of different colors, with said colors being chosen depending on what is seen to be mostly fit for the application of the model. Due to the material jetting's ability to use multiple colors at once, this allows for the production of every one of the aforementioned parts with their own distinct colors to be done during the manufacturing process rather than requiring post-processing paint jobs.

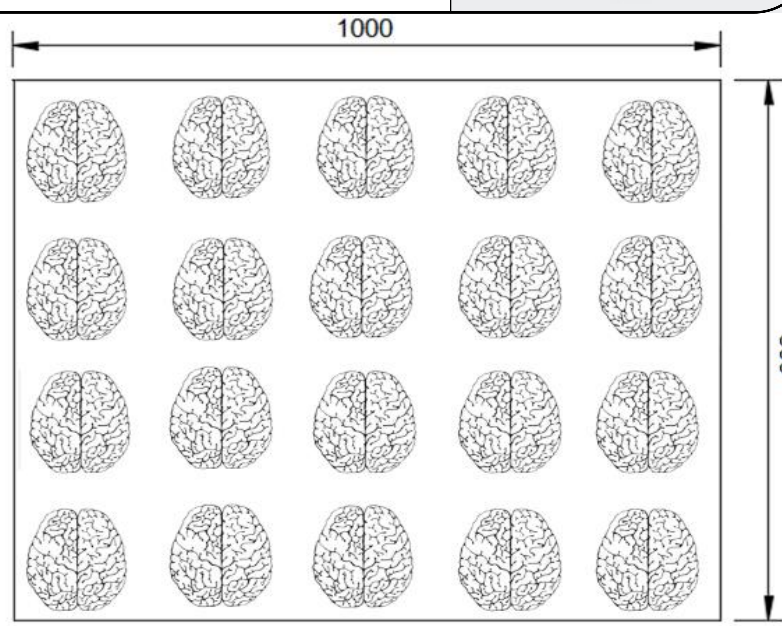
Matte vs. glossy surface texture

Due to the given choice that materials jetting has in terms of the printer's surface texture settings, consideration has to be made into which one would be more suitable for the product. In terms of the brain model, it's main application of it is to be able to demonstrate the brain rather than be aesthetically appealing, as such, a shiny and extremely smooth surface finish is not required, in actuality it would be worse, since if it were to be shiny it could reflect light during demonstration which could potentially be detrimental to the function of the product. On the other hand, the matte print setting has the added benefit of resulting in better accuracy due to the print setting causing the surface of the print to be more uniform compared to the glossy setting. As such, it is fair to say that the matte surface texture print setting would be more suitable and overall more beneficial for the product.



Build volume

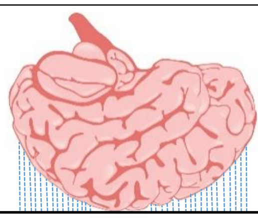
As stated by (Winston Medical Center, 2021), the dimensions of an average brain is about 167x144x93mm, while the build volume of material jetting printers can be as big as 1000x800x500mm, as such, on average this would allow for the manufacturing of 20 models at the same time. However, as mentioned earlier, due to the models being tailor-made for the patient, this means that not many models would be produced at the same time, nonetheless, the bigger print size does permit the production of models for multiple patients during one print cycle.



Support optimization

Due to the removal process of the support material causing a lot of damage to the overall surface quality of the product, as well as that, the support material can't be reused and as such they're solely waste. As such, the orientation of the product while it's the print stage needs to be thought beforehand to be able to minimize the amount of support material that'll be used other than that of the matte print setting's supports. In terms of the model, the best orientation for it to be is upside-down, which is the cause since said orientation is the one in which the lowest amount of support material would be required. Nonetheless, there are still some areas that would still require support structure, however, it would be very little, and it would also be within an area that would be relatively easy to smoothen out during the finishing process due to it not being obstructed by anything.

Orientation



Potential material of choice

One of – if not the most – important aspect that needs to be considered is the material that is going to be used for manufacturing the product, as the material is the determining factor for the product's properties and characteristics as well as its aesthetic appeal. In terms of material jetting, the manufacturer should bear in mind the quantity and cost of the material as well as that the variety of material choices is rather limited, however, application specific resins are nonetheless available.

Brief of potential materials

The following materials do not represent all types of photopolymer resins that can be used with material jetting technologies, however, they are the most likely candidates to be chosen for the final build of the product. Information given for the material is credited to (Varotsis, 2021).

Standard resin	Flexible resin	Simulated PP resin
Standard grade resin used with material jetting processes is characterized with being non-flexible, it is also known for feeling similar to parts that have been made with the use of injection molding technologies. The major drawback to this type of plastic is the fact that it's fairly brittle.	Flexible resin – as the name suggests – is very flexible and has is similar in comparison to rubber. The solidity and stiffness of this type of material can also be customized. However, flexible resin is set back due to it being extremely prone to deformations, even so, this issue can be resolved with the use of various method.	This type of resin is able to simulate a lot of the mechanical and physical properties that the polypropylene polymer has, with said properties being that it is rigid and tough, however, just like with the standard grade resin, simulated PP, is relatively brittle and is prone to breaking easily from falls.

Post-processing considerations

Support removal

The support removal is the first mandatory process that would have to be done after the printing process has ended, however, due to material jetting's characteristics this process can slightly differ compared to other additive manufacturing processes.

Post-washing

The post-washing process is done with most photopolymerization based additive manufacturing technologies to wash residue of material on the surface that occur on the surface of the print because of how said printing processes function.

Post-curing

Post-curing is a procedure of applying additional ultraviolet radiation to the print and is done to maximize the print material's physical, mechanical, and chemical properties by linking the polymer particles that were not cross-linked during the initial hardening process.

Finishing techniques

The finishing process is the last step taken during the production process of a print, and is done to enhance either the aesthetic qualities or the physical, mechanical, or the chemical properties of a product by the use of different methods. As such, said procedure is of extreme importance, and because of which, deliberation of the process has to be done to ensure the delivery of the best possible final version of the product. The finishes that are going to be taken into considerations for the final version of the product are the as printed finish as well as acetone vapor finishing.

Finishing

Supports removal

As has been stated earlier, due to material jetting technologies being able to utilize multiple materials, this also allows for the ability to use dissolvable supports by inserting the material used for them within one of the material cartridges. Said dissolvable supports– as stated by (Proto3000, 2017) – can be dissolved by submerging them with a mixed solution of two percent sodium hydroxide and one percent sodium metasilicate, with the rest being water for around 15 minutes, the mixing of the aforementioned ingredients should preferably be done with the use of a specialized cleaning tank. This is extremely important as although the dissolved supports would be wasted, however, they would not damage the surface's quality. Although the price of dissolvable supports is higher than that of normal ones, the advantage they provide way outweighs their drawbacks.

Post-washing

The post-washing process is a crucial step that has to be done when printing any photopolymer-based resin print. The print has to be washed due to the wax like surface texture that material jetting prints have subsequent to the finishing of the printing process, which is caused by the supporting system that many material jetting machines utilize. The method in which this process is done by applying heat, either through steam or by traditional heating methods to melt the wax like surface off, however, some remnants of it might still be on the surface finish, and to make sure that there isn't and residue remaining what is done is that the surface is simply scrubbed with a cloth soaked in a 70-99.9% isopropyl alcohol (IPA) solvent.

Post-curing

Overall, the post-curing process can be quite time consuming and costly because of the expenses that are associated with the post-curing chamber that is required to efficiently post-cure prints. However, according to (Varotsis, 2021), due to the very thin layers that material jetting printers deposit – which are approximately around 16-32 microns – the post-curing process is not required since unlike other additive manufacturing technologies that utilize photopolymerization, most of the polymer particles would have already been cross-linked during the initial printing process when the material was first being deposited and cured.

A post-curing chamber

Aesthetic finishing

As printed surface finish

Due to the nature of how the product is going to be used, is very likely that it won't require a finishing technique to done for the surface of the print, which is mostly attributed to material jetting prints' natural surface finish being already very smooth right out of the printer. As well as that, on account of the technology being able to use dissolvable support material, no damage to the surface would be done during the support removal process, and as such, no additional finishing would be required to remove the damage that the support material would normally inflict upon the surface of the print, as well fewer expenses being spent for finishing due to no labor or equipment expenditures being required.

Sanding

As mentioned in the 'As printed surface finish' section, the product is most likely not going to require further finishing, however, if it were deemed to be necessary for certain parts of the product, sanding would most likely be the most suitable option, due to it being able to smoothen out the surface and also due to it being cheap and a safe way to finish the product without potentially damaging it unless the wrong sand paper grade were to be used. The sanding process would be done with the use of a sanding belt as that would be the fast and most efficient, however, it still does tend to be relatively slow.

Powder Bed Fusion

Product 2 – Luxury Watch Cases

The case of a watch is the main body and enclosure of a watch that houses the main segments of a watch such as the movement and the dial.

Requirements

Aesthetic appeal	Durability	Dimensional accuracy
Nowadays, as a consequence of cell phones, physical watches are not considered as much of a time keeping tool as they have used to, but rather as an accessory, and as such, aesthetic appeal is the priority when it comes to the design and look of a luxury watch case.	A watch case has to be durable as in it has a high resistance to wear from oxidization, should be very scratch resistance as to not show any marks after the watch has been worn for a long period of time, and should also be strong as to not dent or break easily.	Watch cases need to be of extreme dimensional accuracy to be able to tightly house the movement without any sort of shaking within the case. Also, due to the seemingly absurd pricing of luxury watches, consistency among the brand is certainly to be expected from the manufacturer.

How PBF technologies work?

In terms of the full operation that powder bed fusion technologies utilize, it certainly differs from on type of process to another, however there is one aspect that almost all said technologies have in common, which is the coating process of the build bed, which would be the one that is mainly discussed within this section.

Before the process starts, 3D digital CAD model that would be the design of the printed product has to be send to the printer or installed within it, following that, the powder is heated and then the main production process starts by coating the entirety of a build platform. The bed is coated by a powdered material and is done with the use of a roller that gets its powder from a feeding chamber that pushes the powder from a platform separate to the building bed to the front of said roller. Subsequently, the roller pushes the powder from one end of the build platform to the other which as a result coats it and provides the first layer of the product.

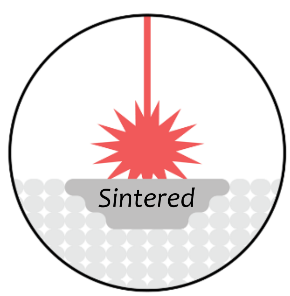
After the coating the process has been done, a high energy thermal source which differs from Powder Bed Fusion technology to another is directed into the mentioned powder, which consequently leads to the fusing of the powdered particles. Following the fusion step, the bed is lowered one layer's height and the entire process is repeated until each layer of the product has been produced.

After the product has concluded printing, due to the re-coating process coating the entire surface of the bed rather than specifically the section that is required for the product, this leads to a significant amount of the powdered material being all around the print that would have to be removed, however, the procedure in which the powder is removed does differs from one type of Powder Bed Fusion technology to another.

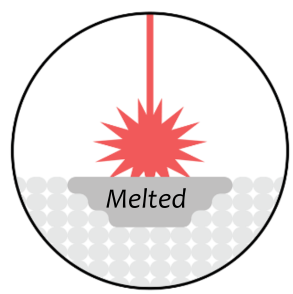
Types of PBF technologies:

The number of powder bed fusion technologies constitute of five, with them being SLS, DMLS, SLM, EBM, and MJF. However, both SLS and MJF printing technologies are exclusively used for polymer based printing, while luxury watch cases are patently a metal based product, and as such, said technologies would be excluded from the report.

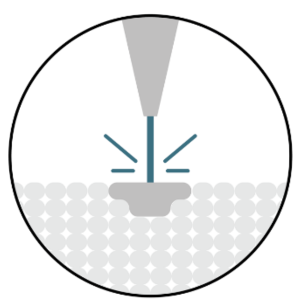
DMLS



SLM



EBM



Main – DMLS and SLM

SLS, DMLS, and SLM Powder Bed Fusion technologies all follow the same process principles, with the only differences being in the material used and thermal source's temperature, and as such – to avoid repetition, the main process would be explained within this section with the differences being within a separate one.

After the initial bed coating process concludes, a high power thermal laser is directed at the powdered material on the bed, said laser either being a carbon dioxide or a fiber glass based. When directed, the laser traces the geometrical shapes of the required product, this is done by The method in which the laser traces the shape of the product is done by using a galvanometer, a type of motor that controls a set of mirrors known as galvos. The laser gets aimed the galvos and consequently gets redirected towards the bed, while during this the mirrors move to allow the laser to trace the dimensional shape of the product. Consequently, the powder that the laser has been aimed at is fused to together, which thus creates a layer of the product. After said process has finished, the bed is lowered and the process is then repeated until the entirety of the product has been printed.

DMLS

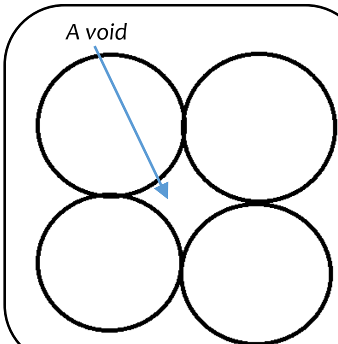
Direct metal laser sintering (DMLS) technologies fuse together metal powder particles by sintering said particles together to create a solid object. According to (AZO Matieral, 2016), the process initially starts by inserting an inert gas within the build chamber to decrease the rate at which oxygen is produced, which consequently also decreases the likelihood of oxidization. As stated by (Redwood, 2021), DMLS printing technologies are unlike polymer based PBF technologies they require support structures due to it being a metal based PBF technology. The reason to that is mainly due to the material that's being used being relatively heavy, and also due to the residual stress that is applied to the material which is attributed to the high powered laser being utilized to fuse the powder particles, which cause the need of support structures. This isn't the case due with polymer based PBF technologies due to the powder surrounding the product being fit to act as supports. As such, due to the requirement of support for overhanging surfaces, the surface quality of the prints would be affected negatively during the removal process of the support material.

SLM

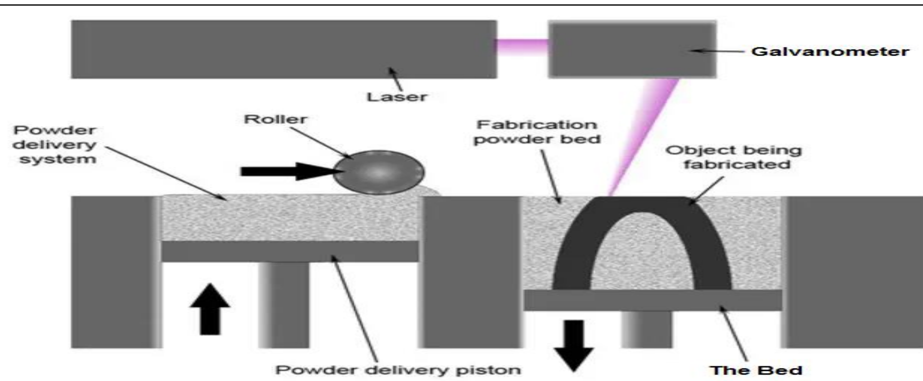
Just like with DMLS technologies, Selective laser melting (SLM) processes start by applying an inert gas to prevent oxidization as this technology as well utilizes metal based powders for their prints. However, SLM differs particularly in the way that it fuses the powdered material together, in which that unlike DMLS, SLM printers melts the powder to fuse powder particles together, and as such it also uses requires a higher powered laser than the ones being used in DMLS printing technologies to be able to reach melting points, rather than sintering ones. As stated by (Rapid Made, 2014), melting the powder helps with preventing potential failed prints and generally creates a stronger product as it reduces porosity of the material like the one seen when a sintering fusing approach is taken. However, unfortunately, just as with DMLS printing, due to the higher residual stress being caused by an even stronger laser as the material in this technology is being melted rather than sintered, and due to it also being heavier, dedicated support material would be required as the powder alone would not be sufficient.

What is sintering?

Sintering is the process that is used in DMLS printing, and is done by compacting a powdered material together with the use of pressure and then heating it to a temperature point that is slightly lower than the material's melting point, with causes the fusion of an objection without the liquefaction process the melting process have to go through. This is the same process that is used in powder metallurgy. The process occurs due to the effects of the sintering temperature point on the material causing its particles to diffuse which consequently attracts the powder particles together and fuses them. However, the issue with this method is that although the particles are compacted, they do have gaps between them known as pores or voids – as shown in the figure beside this section – which would worsen the material's properties. However, said pore are used as spaces that lubricant particles could fill, which allow for the material to be lubricated more efficiently, such as adding oil the steering wheel of a car.



Diagram



Characteristics of DMLS, and SLM

General characteristics

Accuracy	Surface quality	Capacity	Speed of production
According to (Redwood, 2021), DMLS and SLM printing technologies have a tolerance of around ±0.1mm. The tolerance associated with both technologies is relatively very good, which allows for the printers to be able to cause to print extremely accurate, detailed, and intricate parts. Nonetheless, if more accurate requirements were to be needed, the print speed could be slowed down to allow for a better accuracy that could cause the tolerance of printers to go down drastically allowing for improved details.	As stated by (Varotsis, 2021), the surface roughness that metal 3D printing technologies produce right out of the printer is around 6 to 10µm. Which is relatively bad and is considered a rough surface finish. As such, the finishing process for the products made with the use of said technologies would be more time consuming and costly to get to the optimal surface quality especially if one of the product's requirements is for it to be aesthetically pleasing, and having a smooth surface finish is a major point to achieving an overall appealing product.	The average build volume for DMLS and SLM printers that has been noticed across different manufactures is around 300x300x350mm, with some being around 800x400x500mm which when compared to other technologies on the market, it is relatively mediocre, however, depending on the product, it could be sufficient for the production of multiple prints at once, which would increase the rate at which said product is produced, however, a bigger build volume would certainly be better than the current average capacity of said technologies.	According to (Langnau, 2016), the speed of an SLM printer that utilized two laser for its manufacturing process is around 55cm³/h, with one that utilizes four being around 105³/h, with DMLS printing being a little bit faster since it would take less time to fuse the powder particles. Although the mentioned print speed is relatively decent, the entire process of manufacturing with the use of metal 3D printers is long process due to the time it takes to heat the powder, injecting the inert gas, cooling the print afterwards and the powder removal process after the product has finished printing, which all necessary tasks that have to be done to insure a good quality product.

Capital expenses

When it comes to DMLS, and SLM printing technologies, the price tag for said printers is relatively very large, at a starting price of around 100,000 USD as stated by (Cherdo, 2021), as mentioned earlier when talking about material jetting, this is certainly a huge drawback to the technologies, as starting companies might not be able to afford them and established ones might not desire to invest such a huge sum of money, especially if the product is being produced is of a limited quantity.

Electrical consumption

One of the more notable issues with Powder Fusion Technologies is their extremely high amount of energy consumption. As claimed by (Science Direct, 2018), energy usage of SLM printers can be up to 400-560 MJ/Kg, which is relatively inefficient, and as such would lead to large energy expenses and a harder time sustaining the manufacturing process especially if it was being done in large amounts. The energy consumption values for DMLS printing were not mentioned in the study, however, they would be slightly lower than SLM printing, but would be high nonetheless.

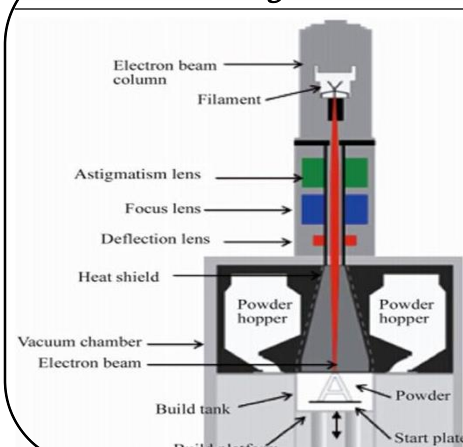
Powdered material

A big issue with Powder Bed Fusion technologies is the fact that the material has to initially be turned into a powder to be viable with the technology, and although this allows for a good variety in terms of material selection, it does nonetheless limit certain material from being used due to them not being able to sustain their functionality in powdered form. Another big issue is also that the process in which material is turned into powder is also rather costly.

EBM printing – How does it work?

Electron Beam Melting (EBM), utilizes – as the name suggests – and electron beam to fuse together the powder particles via a melting procedure. The way that it works is that – as stated by (Kumar, 2014) – generally a tungsten filament is inserted into the machine and is heated until an electron cloud is emitted. According to (Luyk, 2020), specifically tungsten is used due to the material's low thermal expansion and high tensile strength being extremely good as an electron source. An important note to add is that the process has to be done within a vacuumed environment due to gasses potentially disturbing the electron beam, which would cause it to disperse and not move towards the desired location. After the electron beam has been emitted, which can be either one or multiple beams at once, said beam moves through a magnetic field set-up inside the machine which controls the diameter of the beam, after which the beam goes through a second magnetic which consequently directs it to the desired location on the powder bed to trace the geometrical shape of the product, which would melt the targeted area and cause the material to fuse, and as such, a solid layer is created.

Diagram



Characteristics of EBM printing

General characteristics

Speed of production

According to (Kumar, 2014), the higher rate at which powdered material absorbs electrons beams compared to the absorbance of a laser like the one seen in DMLS and SLM printing leads to a faster scanning and fusing speed, which leads to an overall increase in the rate at which products are produced. Also, due to the process being able to utilize multiple beams at once, more section of the layer would be able to be made in one cycle, which also leads to a significant increase in speed.

Build capacity

According to (3D Sourced, 2020), one of the largest EBM printers is 350x350x380mm, which is relatively small especially when compared to the one seen in DMLS and SLM printers which can get to around 800x400x500mm, and other manufacturing processes such as casting due to the ability of using multiple casts at once. And although the aforementioned EBM build volume would nonetheless be able to fit multiple products that are of smaller size, it still leaves a desire for a bigger build volume to be unattended to.

Accuracy

According to (V., 2019), compared to SLM and DMLS printing technologies, EBM has a slightly worse accuracy due to the electron beam that's being produced having a slighter wider diameter than the diameter of the laser being used in SLM and DMLS. As well as that, the powder that's used for EBM printing is less fine than the one being used in said technologies, which also contributes to a lower tolerance which should be around ±0.2-0.3mm.

Surface quality

As has been mentioned in the accuracy section, the use of less finer powder not only results in a worse tolerance, but as well leads to a worse surface finish. As well as that, according to (Kumar, 2014), the surface finish that is produced is equivalent to the one in precision sand blasting finishing processes, which might be good enough for concealed products or applications that don't require aesthetic appeal, however, if the product does need to be aesthetically pleasing, further post-processing would have to be done.

Material selection

As maintained by (Kumar, 2014), due to the main method of fusing the powdered material together being the utilization of an electrical beam, this means that the only materials that would be viable for EBM printing technologies would be good conductive material, and as such, the material selection for the technology is limited to said materials, which would restrict the amount of applications that the technology could be used in. Also, just like with SLM and DMLS, the material would have to first be turned into a powder which

Capital expenditures

According to (Pick3DPrinter, 2021), the general range for an EBM 3D printer is around 100,000 to 250,000 USD, which is an extreme amount of that many companies would avoid due to newer ones not being able to purchase a machine at said price and already established not wanting to invest in a machine with such a price.

Energy consumption

As has been mentioned by (Science Direct, 2018), EBM printing has a great wall plug-efficient as they only consume around 60-100 MJ/Kg, which is deemed to be good energy efficiency. This is extremely helpful especially when having a manufacturing process with that is used for the production of a relatively large quantity.

Support Material

As stated by (AMFG, 2018), just like with DMLS and SLM printing technologies, EBM does require support structures due to the weight of the material that's being worked with, however, the amount of residual stress that's being applied to the material is less than the one being applied within DMLS and SLM printing, and due to that, less support structures would be required to efficiently support any overhanging sections of the print.

EBM ← **As Print Surface Quality** → SLM/DMLS

Most suitable PBF technology for the product

SLM or DMLS

The main aspect that differentiates SLM and DMLS printing technologies is the fusion process, with SLM printing melting while DMLS sintering the powder. The fusion process effects the polymer particles in that sintering fusion approaches generate a higher porosity while in contrast a melting approach generates a relatively very low porosity percentage. As mentioned earlier, a high porosity is helpful to product that are meant to be lubricated in regular bases as it helps with achieving a more efficient lubrication, however, said high porosity also decreases the material's different properties.

In terms of luxury watch cases, the product does not require lubrication whatsoever, and as such, having a higher porosity does provide any usefulness to the product, but rather all it does is weaken the material's properties. As such, between SLM and DMLS printing, SLM printing would be a more beneficial choice over the two due to the lower porosity percentage that the printing process generates.

↓

SLM

↓

SLM or EBM

The main advantages that SLM printing has over EBM technologies is that it has a better accuracy due to the powder being used having a finer grain, as well as the diameter of the laser being smaller than the electron beams that is being used in EBM printing, which, in terms of luxury watch cases is a really important aspect since great accuracy has to be achieved. Another main advantages point that SLM printing has over EBM is that fact that it produces a better surface quality right out of the printer due to the Ra value of SLM being around 6-10, while EBM printing has a surface roughness that is relatively slightly higher than that of SLM. Meaning that longer time would be required to finish an EBM printed product compared to SLM, it would also lead to a more favorable final finish for the watch's case overall. Another big drawback to EBM printing is the technology's relatively low material selection since the only materials that are viable are conductive materials.

In contrast, the main strengths that EBM printing has over SLM are that the technology has an overall faster printing speed which is a consequent of the printer being able to utilize multiple beams at once and due to the faster absorption that materials have of an electron beam over a traditional laser like the one being used in SLM, which would overall increase the production rate of the product, however, due to the limited amount in which luxury watches are produced, a faster rate in production would not be extremely beneficial. Another big point with EBM printing is the requirement for less supports, which would help with preserving the quality of the surface finish, however, overall, SLM printing still does have a more required finishing roughness. As well as that, EBM printing consumes less energy overall, meaning that electrical expenses with the use of EBM technologies would overall be lower than if SLM printers were to be used.

In conclusion, although EBM printing processes do certainly have evident advantages over SLM printing with them being the energy consumption and speed of production, however, said advantages are relevant to the product as much as the strengths that SLM printing technologies possess, which are the printer being able to produce relatively very good accuracies, and also having a better surface finish, which are both advantages that are beneficial to the product, due to luxury watches cases requiring aesthetic appeal and good dimensional accuracy for a perfect fit of the watch's components.

↓

SLM

↓

Conclusion

In terms of SLM printing technologies or DMLS, the difference between two printers and the product that they produce is marginally small on the surface, however when a closer look is taken at the print on a molecular level, the ones that are produced with the use SLM printers have fewer voids between their particles due to the melting approach that's taken, and as such less of the material's properties is sacrificed, and since said voids are used for lubrication while luxury watch cases do not require any, therefore SLM printing is the better one out of the two for the requirements of the product. In terms of SLM or EBM, both have their own strengths of limitations that contrast each other, however, the strengths that EBM printing possesses over SLM such as the printing speed and lower energy consumption, it doesn't outweigh the ones seen in SLM like the better accuracy and surface quality. That is due to luxury watches requiring a better finish and are more focused accuracy and since they are only manufactured at a limited quantity, the element of speed isn't of importance. As such, out of all three metal based PBF technologies, SLM printing would be the most preferable and suitable one for the purpose of manufacturing luxury watch cases.

Product justification

Strengths of SLM printing

*The main advantage that SLM printing technologies have over CNC machines – CNC being the general way that watch cases are manufactured – is the fact that the technology is able to overcome many **complexity** issues that CNC machines might not be able to such as undercuts, cavities, and inner features. In terms of the wach cases, although the general design of a watch case is rather simple, if additional details were to be added, it could potentially be extremely challenging to do with the use of CNC, however, said issue is not a point of concern when working with SLM printers. Another major point is the **accuracy** for SLM printers could be way better than the ones that CNC machines have. That is the case since SLM printers have a starting tolerance of ±0.1mm, while CNC machines being at around ±0.127. The difference isn't big, however, as has been just mentioned, the ±0.1mm tolerance is only the starting – or the general tolerance – of SLM printers, although if they are slowed down they can be much lower and would outweighs the ones that CNC machines provide by a significant amount, even after the finishing pass of the CNC machine, this aspect is really important because as mentioned earlier, the quality of manufacturing and consistency among the brand – especially in the case of luxury watches – is really important. Another important aspect of SLM printers is that they are relatively easy to operate compared to CNC machines, since the slicer program the operates the printer is easy to use and all is required is to install the digital model, while CNC machining, especially with more complex products requires a lot of training especially to program the tools, which can take a year or even more to learn. The **lead times** required for SLM printing are also relatively little, with all that has to be done is just loading in a sufficient amount of the powdered material for the product into the chamber in which the material is held in within the machine, check that the machine has enough inert gas, and then simply load the CAD model into the printer and allow it to run. However, as stated by (CNC Cookbook, 2019), setting up a CNC machine is a much more time consuming task, due the process required to set-up the CNC machine's tools to the required lengths and diameters. Also, due to the relatively low lead time that SLM printing requires, redesigning the product would not be a major issue, as the only thing that is required to be changed is the CAD model, unlike CNC, which would also require the change of the CAD model as well as redoing the setting process for the tools, the **cost of said tools** is also relatively expensive, while SLM printing doesn't requires any secondary tools, as such SLM printing is more flexible in that regard.*

*A major point add is that SLM printers are superior than CNC machines in is the **capital price**, since although the price of industrial level SLM printers is around 100,000 USD, according to (Maes, 2021), entry level 5-axis CNC machines – which are the CNC machines that are required to create very detailed products – start at 200,000 USD, which is double the price that entry SLM printers are at, not only that but the tools that are required to make complex products can be very expensive which also adds to the capital price of the machine. Another factor that increases that cost of sustaining a CNC machine relative to SLM printer is SLM printers produce very **little waste** since said waste only comes from the support materials and any finishing process processes that might take off some of the material, while a subtractive manufacturing technology like CNC machining would produce a lot of waste due to the cutting process of the block of material, which is bad from an environmental point of view and also bad in terms of that said waste causes a lot of expenses that the company would have to deal with, especially if precious metals such as silver, gold or platinum were to be used, which certain watch manufacturers do utilize for their cases.*

Weaknesses of SLM printing

*One of the main disadvantages of SLM printing relative to CNC machining is the surface quality, that's the cause since SLM printing produces prints at a relatively bad surface quality of 6-10µm, and although the surface quality of products that have just came out of the CNC machine are also relatively bad as according to (Varotsis, 2021), they have an surface roughness of around 3.2µm, and would also have several rough tools marks from the machining process. Nonetheless, it is still way better than what SLM printers produce right out of the printer, the surface roughness of products made by CNC machines could also be easily improved by allowing the machine to work through the case one more time, but at a lower speed, which would improve the products dimensional accuracy as well as the surface finish, however, in terms of accuracy, SLM printers are still superior. Overall, this means that more time and effort would have to be spent to get the necessary surface quality for the product in SLM printing compared to CNC especially in the case luxury watch cases where the surface quality is of major importance. Another important point to mention is speed, that is the case since CNC machines are relatively very fast at a speed of approximately 5850cm per second, as was stated by (OSWALD, 2020). While in contrast, as has been mentioned earlier, the SLM printing process is not. Although the speed and volume of production is important, in the case of manufacturing luxury watch cases, it isn't the priority due to the small quantity that's required, and as such, although SLM printing is slower, that fact wouldn't affect the product as much, however, it still is a drawback to SLM printing. Also, even though SLM printing has a wide selection of materials, the variety is lower than that of CNC machining due to CNC machining not requiring any pre-processing to the materials like in SLM printing, which requires for the material to be turned into a powder, and as such, some **materials might not be suitable** for the process. As just mentioned, the material would have to be initially turned into a powdered form, and the process of doing so is relatively costly. It is also important to note that SLM printed products are susceptible to warping, which an issue that CNC machining does not have to worry about as much unless the settings were not optimized appropriately. However, according to (Varotsis, 2021), if supports were to be used on warping prone section, it could help reducing the magnitude at which the warping occurs, nonetheless, the removal of said support material would worsen the surface quality of the product. It should also be mentioned that to realize the advantage that a technology like SLM printing provides, the 3D **CAD model would have to be optimized** to fit the requirements of printing the product with the advantages of the printing technology such as being able to print the entire product in one printing process without having to join separate parts of it.*

*As mentioned earlier, SLM printing outweighs CNC machining in terms of capital expenses and waste sustainability, however, one element that SLM printers really struggle in is the **energy consumption**. And that is very evident when compared to CNC machining. As stated by (Murphy, 2015), CNC machines consume 1kwh, which is extremely lower than SLM printing's 400-560Mj/Kg. As such, in terms of electrical expenses CNC machining is greater than SLM printing by a significant amount. Another expense of SLM printing – as mentioned earlier – is the process of turning the material required for the product into a powder.*

Lastly, due to the melting approach that SLM printers utilize – although in small amounts – pores would still generate between the powder particles, which would decrease the effectiveness of the material's properties. While this issue is absent when working with CNC machines due to the process working with solid blocks of materials. As such, the material properties of SLM printed cases would be worse than ones made with the use of CNC. However, the difference would not be very significant, and probably even negligible.

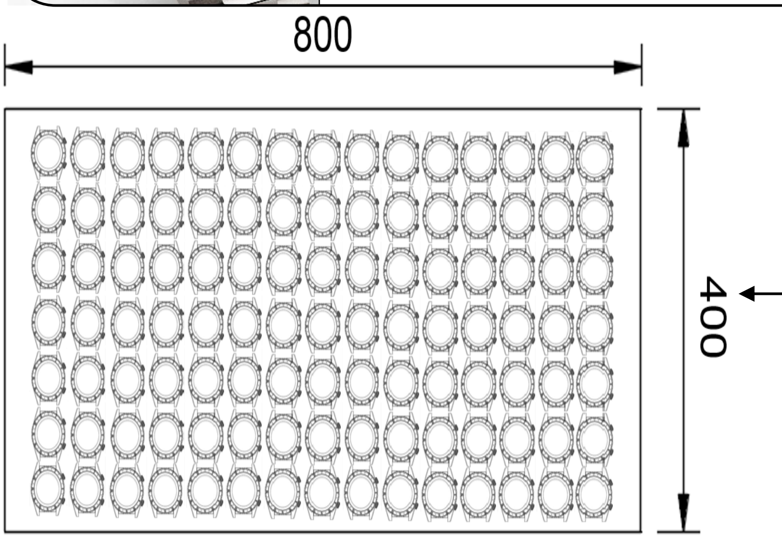
Design considerations

Intricate details

One of the main points that make the difference between a good and an excellent watch case is the little details found within the case, this could be anything from engravings that are found at the outer layer of the case or inner details over the dial that can be seen through the crystal. Due to SLM printing technologies being able to create details with extreme accuracy without requiring any extended labor, this feature should be taken advantage of, and consideration of further details should be made in order of doing so.

Case and bezel simultaneous printing

The method that most watch manufacturers utilize in terms of joining the watch case with the bezel (the part surrounding the top of the watch case) is by making both pieces separately and then fixing the two together since it would be difficult to join both section during the manufacturing process. This procedure requires more times as well as more money for the joining equipment expenses. However, due to SLM printers being additive manufacturing technologies, this allows for the machine to bypass the limitation barriers that prevent both section from being printed together. As such, unless the bezel is made with the use of a different material, printing both the case and the bezel at the same time should be an important point to think through and potentially execute.

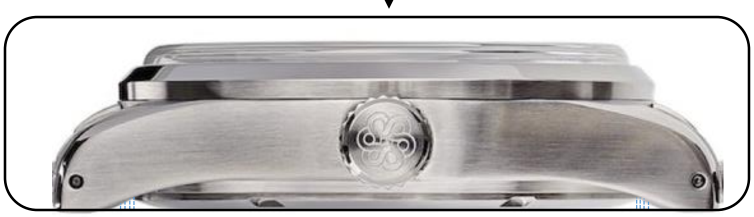


Build volume to product

In general, the case width of watch cases is usually between 36-42mm, while the lug to lug width being around 42-49mm, (the width used for the diagram is 38mm case width with 45mm lug to lug) as such, with a build volume that can be as big as 800x400x500mm, the amount of watch cases that can be done during one cycle is approximately around 105. However, as has been mentioned earlier, due to the nature that the luxury watch market works, a huge production rate is not required. As such, although the amount is small relative to a general industrial scale, the aforementioned amount of production is nonetheless deemed to be sufficient.

Supports optimization

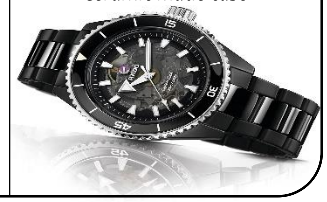
If the watch case were to be placed on its normal – standing upwards – orientation, there wouldn't be any overhangs that necessitate support structure for the exception of the crown guards and if raised or arching lugs were to be implemented into the case's design. Nonetheless, the surface area of said possible implementations is very little, as such, this means that either very little support structures would be needed or none at all during the printing process of the case, which consequently leads to an overall better surface finish that would require very little further finishing caused by support removal damage.



Potential material of choice

Due to the many types of materials that SLM printing technologies are suitable with, this means that manufacturer has a variety of material that they can choose from, one of which being ceramics, a material known for being generally hard to work with and machine with the use of different manufacturing method other than SLM, is a type of material that is characterized for being very wear resistant even after many years of use, as well as scratch resistant which is an attribute that is especially required for watch cases, and also being a relatively light material. As such, the use of a type of ceramic, as well as its price and amount should be taken into account during the process of deciding the material of choice for the case.

Ceramic made case



Post-processing considerations

Powder removal	*Supports removal*
The first step to be done after the printing process has concluded in powder bed fusion processes is to remove the powder surrounding the print to be able to collect the product as well as reuse the un-utilized powdered material that has been deposited by the printer.	*After the print has been removed from the powdered material, the second procedure to be done is to remove the support structure that would be found under overhangs of 45 degrees or more and bridges.*

Finishing techniques

As mentioned in the material jetting section, the finishing process of a product is the final as well as one of the most important aspect to the production procedure. Due to SLM printing working with metals the finishing techniques that would be taken into account to be used for the final product are blasting, traditional grinding, and brush finishing.

Finishing

Product collection process

1. Powder removal process

The powder removal process is either done with the use a brush or a vacuum cleaner, after which the material is cleaned with the use of an air blower to make sure there isn't any residue of the powder remaining on the surface. Although the process itself is rather straightforward, strict safety precautions must be taken due to the ease at which the powdered material can be inhaled, which would consequently cause potentially life threatening medical issues. As such, during the process the user must at all times wear a respiratory mask as well as safety goggles.

2. Supports removal process

The process of removing the support material is simply done with the use of pliers. The main issue other than the surface damage that comes with this process is the time consumption, especially if a product has many overhang, also certain parts might require thicker and sturdier supports which would be harder to remove. However for watch cases that shouldn't really be a major issue since as seen earlier, not many supports would be required for the product.

Aesthetic finishing

Polishing

A polished finish provides the watch case with an attention grabbing light reflective mirror-like finish, however, if scratches were to be made, they would be easily seen. As stated by (Prisma, 2021), this method is done with the use of a polishing wheel, and the type of polish applied differs depending on the material it's being applied on. Although this method can work on a variety of materials it is most viable when used with stainless steel or precious metals such as silver, gold, and platinum.

Blasting

Blasting – or also known as sandblasting – is a process done by launching a stream of tiny sand grains at extremely high speeds. According to (Prisma, 2021), this finishing method gives the case a matte and non-light-reflective surface that is able to hide relatively small scratches better. Although this type of finishing does not make the watch conspicuous, it does however give a smooth and clean look to the case that might either be liked or disliked depending on the consumer.

Brushing

As stated by (Prisma, 2021), a brushed finish is the process of brushing the case of the watch with the use a steel brush. Just like blasting, this gives a watch a matte and non-light-reflective surface, which when compared to a polished finish, is able to hide scratches much better. This type of finishing also leaves straight lines marks on the surface that are caused by the brush, which is meant to give an aesthetically appealing look although some consumers are not fond of the brushing marks.

Conclusion

*Out of the three aforementioned finishing techniques the most attractive one is **polishing**. That is the cause since although it is more prone to showing scratch marks, it also looks the best out of the three which is the aspect that hold the most importance. That is mainly due to the mirror like surface that it provides, while brushing and blasting look dull to a certain extent. Even so, if minor scratch marks were to be seen on the surface, the user is able to easily polish said marks off, while large scratch marks would be evident no matter the finishing technique that it utilized. As due to that, the advantages that polish finishing yields outweighs its disadvantages and as such it is deemed to be the most suitable finishing process to be utilized.*

CAD Modeling methods

The CAD modeling process is the initial task required to start the product of any 3D printing process since the printer requires an STL file of a 3D design to be installed within it for it to start printing. There are mainly two method in which the this process is done, one is by designing it with the use of a 3D modeling software, while the other being the utilization of a 3D scanner.

3D scanning

A 3D scanner is a device that allows the manufacturer to simply scan the object they are intending to produce by turning the device around it for a certain amount of time that is usually around 2 minutes or so. After which, - according to (KIVOLYA, 2019), accurate dimensions of ±0.1-0.01mm and shape of the object are transferred into a CAD modeling software, which then allows the user to adjust the model to their will. The obvious drawback to this technology is that it only works with already existing products, as such, if a nonexistent design were to be required, this method would not be viable. As well as that, the other major disadvantage to 3D scanners is the expenses of owning one, with the starting price being around 3,000 USD – also as stated by (KIVOLYA, 2019) – which would limit the accessibility to the technology for certain manufacturers, however, certain 3D scanning have been recently implemented into newer generation iPhone operating systems.

Manual 3D modeling

In contrast to 3D scanning, manual modeling is the process of using a digital CAD modeling software such as AutoCAD, Maya, Sketchup, Rhino, and many more to manually design the product from scratch, said softwares also offer many useful tools to ease the designing process, however, the difficulty of it highly depends on the product itself, and in the case of a brain model and a high-end watch case, the whole procedure would be extremely challenging, and would require knowledgeable people with a lot of experience in digital modeling, said people would generally demands high wages, which is something that should be kept in mind. It is also important to note that the expenses of licensing some of the aforementioned softwares could also be relatively high.

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"I don't have a crystal ball that tells me what things are going to happen, but I know this: when you get enough smart people working on something, it always gets better"

-Chuck Hull

Initiator of 3D printing technologies