Additive manufacturing

The technology of the future

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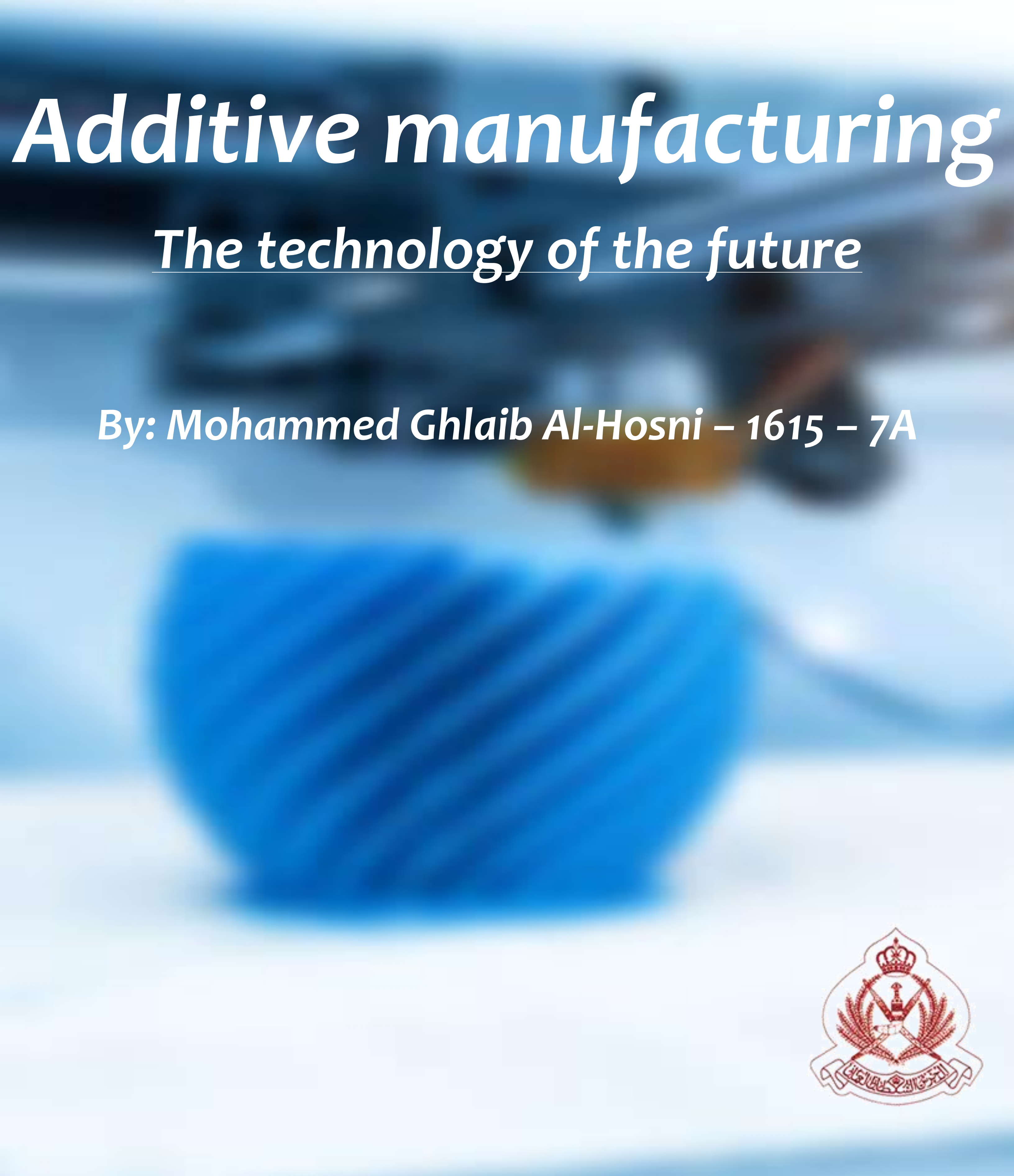

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Report aim

The main aim of this report is to be able to convince a manufacturing company manager by assembling a compelling argument on why two separate products would greatly benefit from additive manufacturing processes, specifically, FDM and SLA printing, and why additive manufacturing would be better than the current manufacturing process that is used to produce them.

Prosthetic sockets – FDM

What is it?

In prosthetics, the socket is the part responsible of joining the amputated section of the leg to the rest of the prosthetic and is also where a lot of the body weight would be put on. The prosthetic would need to be unique and custom-made for each person. (1)

Materials	Requirements	Current technologies
Prosthetic sockets are most commonly made using polypropylene although they are not limited to that since polypropylene could be replaced for sockets by other materials such as nylon and PTFE. (2)	*Due to prosthetic sockets being a daily use item they would need to be extremely durable and corrosion resistant and would also need to be tough and be able to withstand a lot of force. The socket would also need to be accurate since they would need to fit the user comfortably.*	*Currently, the main way to produce prosthetic sockets is moulding, specifically a moulding method called bubble-form moulding, what happens is that a thermoplastic material is heated unit it becomes a stretchy sheet of material, after that the material is placed wrapped over the mould and left to harden. (3)*

Chess set – SLA printing

What is it?

A chess set is a collection of 32 small pieces that are divided into two colors. Said pieces possess 6 different unique designs consisting of the King, Queen, Bishop, Knight, Rook, and pawn pieces and are used to play a popular two player board game known as chess.

Materials	Requirements	Current technologies
Chess pieces can be made out of numerous materials such as metals, glass, ivory although they are most commonly made using either polymers, specifically polymethyl methacrylate (4) because it is generally a cheap material to make them with and also with wood due to it being durable and aesthetically pleasing.	*A chess piece mainly requires two qualities, and that is for the piece to look aesthetically pleasing and for it to have a good and smooth surface finish since the piece would be touched a lot by the player and having good tactile attributes would make it more comfortable to play with.*	*Plastic chess pieces are usually made using injection moulding for a fast and efficient manufacturing method (5), while professional wooden chess sets are generally hand crafted to by skilled carpenters to achieve the topmost quality. (6)*

Introduction

Brief

Additive manufacturing is the process of creating a product from scratch layer by layer by using digital CAD models and slicing them into thin slices using a slicer software, said sliced models are then "printed"/placed using a 3D printer. This is done by placing those thin slices layer by layer on top of each other and hardening them before placing the subsequent layer, the method of hardening and placing those layers differs from one AM technology to another. AM used to be for creating models for bigger products that are eventually going to be made using alternate methods, although the technology improved with time and nowadays it is even used to make fully fledged products.

Why use additive manufacturing?

Complexity

Using additive manufacturing, the user can make much more geometrically complex shapes with much more ease, as the start of the additive manufacturing process begins with making a 3D CAD model, and with that, you can much easily edit, design, and add items or details that might prove to be extremely difficult with other manufacturing methods due to the geometrical limitation posed upon said manufacturing methods such as moulding and subtractive manufacturing. Such complexity issues could are cavities, undercuts, inner features, details, and more. That is the case because due to additive manufacturing making the entire product layer by layer from the ground up, and thus, all features of the product would be made at once, therefore, bypassing all of the mentioned complexity issues that other processes struggle with.

Waste

Another one of the main advantages of additive manufacturing is the lack of waste or at least how relatively little it is. That is the case because as mentioned the product is built form the ground up layer by layer, meaning that every layer of the product would be placed without the need of any extra material to be used up, and thus leading to an exceptionally well waste-efficiency and very little waste being produced except for the support material which will be discussed further on in the report. This point is of extreme importance as wasted material means nothing but wasted money, and due to the extremely low amount of waste being produced from additive manufacturing process, a lot of money would be saved if additive manufacturing technologies were implemented. Some waste that comes off of certain materials could be harmful for the environment, therefore, producing less waste consequently results in a more environmentally friendly production method.

Materials

Contradictory to the belief of many, additive manufacturing is not used for polymer product manufacturing only, but rather, many other materials, such as metals, ceramics, composites, and even woods. This extremely important since different products would require different materials. Also, some of the mentioned materials might not be viable for certain AM technologies, meaning the requirements for printing said materials might vary a lot in price, machine room size, sustainability, etcetera.

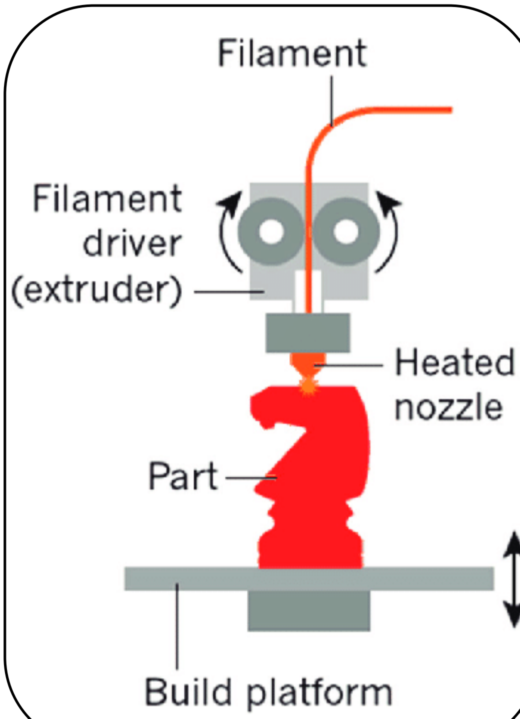
Uses

Additive manufacturing has many different uses in many different fields, such as aerospace and automotive for manufacturing engines and certain aircraft parts, to dental and medical to produce eruption guides and caskets, and even to footwear to make shoe soles and flip-flop sandals.

Fused deposition modelling

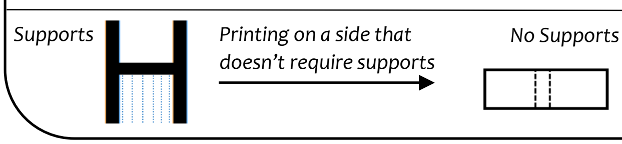
How do FDM printers work?

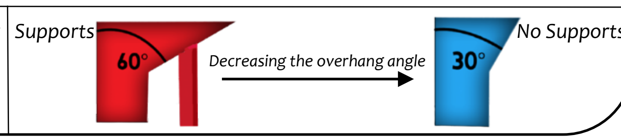
FDM is an AM technology/machine that is only viable with thermoplastics. The way it works is that a thread of thermoplastic that comes in spools is inserted into an extruder, which reels in the thread towards a chamber right before the nozzle, inside of said chamber the thermoplastic is heated until it is in a semi-solid state. After being heated, the plastic then goes through a nozzle and onto the platform where the product will be made, also known as the bed, when the plastic does hit the bed, it will be cooled down via a layer fan, and due to the plastic already being in a semi-solid form, the layer fan would be sufficient enough to harden it quickly (7). Then this process is repeated until the product is done, during it, either the bed or the nozzle itself moves horizontally and vertically to create the geometrical shape of the product and up and down for the height. Furthermore, during the printing process of certain types of plastics, the bed could be heated by the printer itself, this is done to keep said plastics warm even after they have placed on the build platform as it would help out a lot in keeping certain polymers from warping and also with adhesion.



Support structure

Support material is the structure used to act as a base for overhanging sections of products, thus allowing said sections to be placed when they are in the process of being printed. The common rule for support structure is that it is necessary for any overhanging sections of the product with an angle of over 45 degrees. Support structure is generally unwelcomed as the process of removing the support structure would damage the surface finish of the product where the support structures used to be, although there are certain types of support material that are dissolvable when placed in water, said types require expensive FDM printers that contain more than one nozzle. As well as that, support structure isn't part of the main product, meaning that any support material that is used up is generally seen as just waste. However, there are two main ways that can be used to avoid support material from being required, the first is, if possible, to decrease the angle at which the overhang is at, the second it to print the product laying on a side that would not require support structure if the product is printed on. Although it is important to mention that the methods that were just mentioned might not work with every print depending on the print's specifications.





FDM printing characteristics

Has a tolerance of 0.2mm	Viable with thermoplastics only	Can print multiple materials at once

Strengths

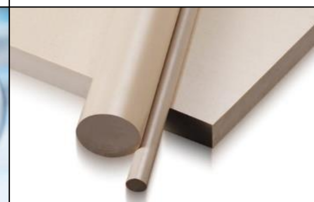
One of FDM printing technologies' main advantages is how relatively cheap it is, that is the case for multiple reason, the first being how cheap entry level FDM printers are and how cheap industrial FDM printers are when compared to other industrial technologies. FDM printing also requires very little training which leads to minimal staff expenses. As well as that, it is viable with a wide variety of thermoplastics, and due to the material it functions with being thermoplastics, that also means that it all materials used with the technology is recyclable. Finally, unlike many other technologies, with the use of multi-nozzle printers, FDM simultaneously print products with multiple thermoplastics.

Weaknesses

FDM printing generally has bad accuracy when compared to other manufacturing technologies, especially when printing small products, and it also has relatively bad surface finish. One major weakness with FDM printing is that due to the nature of how the printer works, many materials that are printed are susceptible to warping which could lead to some dimensional inaccuracy.

What materials are used in FDM printing? (8)

FDM printing has a diverse selection of thermoplastics and is not limited to the following mentioned materials, they are only some of the most popular ones.

ABS	PLA	PEEK	PA12
			
The main reason anyone might want to use ABS is that it is a tough material, thus obviously, it is used for products that required to be strong and durable.	*PLA is environmentally friendly, as it generates no toxic gases since it is fully made using natural materials (corn starch or sugarcane that get mixed with acids).*	*PEEK plastic has an extremely high melting point and requires an extruder that is able to heat over 343°C, meaning you would need a really good & expensive FDM printer for it.*	*PA12 really good chemical resistance, thus it is a good material to be used for any application that involve chemical that would usually damage materials. (11)*
ABS has a higher melting point compared to PLA, and due to that the material is not so viable for products that might require more intricate details.	*PLA is used to make products with great designs and more complex details. That is mainly due to the fact that it requires lower melting points (170°C), making it easier to work with*	*PEEK is around a fifth of the weight of steel and even has a better strength-weight ratio aspect, meaning it is an extremely strong material. (9)*	*The material is expensive with a price of 80 USD per 0.5KG, although this might not be as expensive as PEEK it is still expensive compared to other common FDM filaments.*
ABS has bad UV resistance, meaning of the material is left under sunlight it would start degrading over time making the material less useful than how it originally was.	*PLA is relatively brittle and has lower tensile strength compared to other thermoplastics, meaning it cannot if the application requires the material to be under tension*	*The material has an extremely high price tag of about 350 USD per 0.5KG for the filament, making it unpractical for general products with non-critical applications.*	*PA12 is a really good flexible material, meaning it would be really good for applications that would require the product to be able to bend and compress. (11)*
ABS has really good abrasion resistance, meaning that it would be good material for products that might get heavily used as it won't get scratched easily.	*PLA is very cheap, at around 30 USD for 1KG, meaning it is a practical use for any random or small personal creations as you wouldn't want to spent lots of money on them.*	*The plastic would work really well for any application that involve water since it has good water absorption resistance and can go even go over 8km underwater. (10)*	*Nylon 12 is has very good thermal resistance and as such it would prove to be a viable material for the use in application that involve high temperatures.*

Uses of FDM printing

Electrical housing	*FDM printers are used for electrical housing since they're an easy and perfect build for them and that is due to them having a generally simple shape and that plastic is the material used for them anyways.*
Prototypes & Models	*FDM printing is used to create prototypes and models since they are generally made from cheaper material and are also relatively small in size, which goes hand in hand with FDM printing due to it having really cheap printing options and the average printing/bed size is for FDM is suitable with the needs for models and prototypes.*
Personal creations	*FDM printing is majorly used for personal creations such as figurines, bookmarks, random objects, and more, and that is due to the that the entry price for FDM printers being relatively small and also due to FDM printers coming in small sizes which makes it so they can be easily placed in non-dedicated rooms.*

Product justification – FDM

Brief

FDM printing technology is ideal for the manufacturing of prosthetic sockets due to the technology being able to print the main material used for them, polypropylene. Since the sockets are tailor-made for each patient, the large scale manufacturing methods such as injection moulding would not be efficient due to the set-up process for a unique mould being time consuming. There are also many reasons why FDM printing is better than the current technology being used to manufacture sockets, which will be discussed in further detail in this page

Complexity issues

Complexity

Due to prosthetic sockets having a relatively simple design as there aren't any major complexity barriers, this means that the ability of FDM, or additive manufacturing in overcoming said complexity wouldn't be utilized as much although this means that printing prosthetic sockets would take way less time effort from the machine's side. This isn't the case with moulding since moulding is a very long process as it getting an accurate mould with cavity complexities such as the one in a prosthetic socket. FDM is also relatively incomplex and wouldn't require much training compared to other technologies, meaning staff training would be more or less fast and cheap.

Support structure

As just mentioned, prosthetic sockets aren't really a complex designed product, and with that, it doesn't have any major overhangs of over 45 degrees that might require support structures. The only issue might be the cavity where the user would place their stump, although this issue can be very easily resolved by just printing the product standing upwards.

Materials

As mentioned previously, the main material that is used in the production of prosthetic sockets is polypropylene, which is a plastic that FDM technologies can print, although there is a one major compatibility issue when it comes to printing the material using FDM, and it is the fact that polypropylene warps a lot and changes its initial dimensions after the filament cools down and hardens.

Methods of overcoming the issue

This issue can be bypassed in two ways, the first is by using a material that has very similar characteristics to polypropylene. Said material could be nylon, PTFE, or acetal, which are all polymers that could be printed using FDM technologies. If the use of polypropylene was a necessity and changing the material was not an option, then PP could be printed properly by using a high bed temperature of around 100 degrees Celsius (12) and by placing special polypropylene self-adhesive sheets on top of the bed, this could also be improved by applying an adhesion promoter to it to be able to prevent the polypropylene from expanding or contracting. (13)

Cost and Waste

Currently, prosthetic sockets are billed at around 5,000 to 10,000 USD (14), making them an inaccessible option to many people that might be in need of them. But with the use of FDM technologies to manufacture them this would change since FDM machine are relatively inexpensive compared to other industrial technologies, and filament used for the machine is also relatively cheap, making the process of manufacturing sockets way cheaper compared to its traditional method of bubble-form moulding due to the cost of manufacturing the mould. In terms of waste, FDM printing barely produces any waste except for the support material which is relatively little. When it comes to bubble-form moulding though, a lot of material could be wasted when the platic is removed from the mould, that is the case because any extra plastic on the mould would have to be cut off.

Surface quality

Although printed products using FDM don't initially have really good surface finish, the print can be given a very smooth and aesthetically pleasing finish in the post-processing step. In the case of polypropylene, this can be done by sanding the print using a belt sander. Starting with a heavy grit sand paper and going down until the surface of the print is smooth enough for the requirements of the finished product.

Capacity

Although desktop FDM printers might not have enough space to be able to print a prosthetic socket but industrial printers have relatively very big capacity meaning printing size wouldn't be an issue when printing the product.

Accuracy and tolerance

Industrial FDM printing technologies generally have a dimensional tolerance of around ±0.2%, which might not be good enough for prints that require really accurate dimensional accuracy such as prosthetic sockets. This is a major issue although there are two important ways that to resolve it. The first is to print the product at a very slow rate compared to the average time requirement for the print, this can be done by changing the printer's printing settings in the printer's program. The second method of overcoming this issue is to print the product with very small layers. This can be done in two different ways, first way is to also edit the print's parameters/settings, and the second is to use a printer nozzle that has a very small diameter, which would allow you to print even thinner layers. Using both methods would allow for an even more accurate print with a really small error tolerance.

Sustainability – FDM

Recyclability

When it comes to the recyclability of a product, the main factor that determines it is the material used for manufacturing rather than the production process itself, meaning that neither FDM nor bubble-form moulding would affect the recyclability of the product. Thus the main concern when it comes to the recyclability of the product would be the material. In the case of prosthetic sockets, the main material used for manufacturing is polypropylene. Due to the material being thermoplastic, one of the main advantages of it is the fact that it is easily recyclable as thermoplastic material can be melted down and reformed numerous times, consequently, it is welcomed at almost every recycling facility. As well as that, polypropylene has exceptional versatility, meaning that in the case of a badly produced print, the material could very easily be recycled back into filament to be used once again for another print. The same can also be said for almost any other FDM printing filament since FDM works with thermoplastics. When it comes to the support material, although it is difficult to recycle as it is weaker than the material itself, it still can be reused by melting it down by mixing it with acetone, which consequently will turn it into a sort of adhesive that would work well with prints (15). However, there is one major issue regarding the recyclability of bubble-form moulding, is not how recyclable the material used to make the product is, but rather the materials used to manufacture the moulds. Due to the mould being tailor-made, they can't be reused for another patient. Said materials are either polyurethane, silicone, or epoxy. Both epoxy and polyurethane are hard to recycle, however, silicon is easily recycled.

Waste

In terms of waste, FDM – and additive manufacturing technologies in general – are extremely waste-efficient, which is due to the way that additive manufacturing functions, which is producing a product layer by layer. That is the case as when manufacturing a product using FDM printing, each section is built from the ground up with no initial materials as compared to other technologies such as subtractive manufacturing. The only exception to that is the support material, which, as mentioned in the recyclability section, can be turned into an adhesive. The other thing that might be considered as waste is also any material that might be shaved off of the product during certain post-processing methods like sanding. With everything that has been mentioned, it is still relatively very little compared to other technologies. When it comes to Bubble-form moulding, there could be some waste produced when the plastic is taken out of the mould. That is because when the sheet of thermoplastic is placed on top of the mould, the sheet could be longer than the mould itself, and the extra material would have to be cut off, and as such, wasted material is produced.

Energy

Regarding electrical consumption and efficiency, FDM printing is extremely good, that is the case due to the technology's very low energy consumption of around 50 watts per hour on average (16). To put that number into perspective, a decent gaming PC would consume around 300 to 500 watts per hour (17). When talking about the electrical costs of running an FDM printer, if the machine were to be printing for 24 hours a day, and as such, the total cost would only be around,0.2 USD for an entire day. However, when working with a heated bed the electrical consumption does have a big increase and can go up to 150 to 200 watts per hour (16). When compared to the energy consumption of bubble-form moulding, although the amount of electricity consumed by the ovens used to soften the plastic fluctuates from one oven to another, on average it would be around 2.3kWh, which is roughly 0.3 USD per hour (18), and when put side to side to side to the energy consumption of FDM printers, it is significantly higher even if the printer was running with a heated bed, hence, using bubble-form moulding would cost way more in terms of electrical fees.

Localization

The market for 3D printing in Oman and nearby countries has become of considerable size during the past 5 years, with regards to FDM printing, the availability of machines and filaments is wide and a lot of products from many different companies can be found. And in the case that certain items might not be found here, they are most likely to be located in the UAE, and if ordered from there, the shipping is extremely cheap and is only around 4 days at most, making the issue of transportation almost insignificant, It is also fairly easy to get spare parts for printers from the UAE, meaning that in the case that an issue occurs to the printer, finding parts to fix it wouldn't be a major issue. The same could be said about the issue of localizing the product's manufacturing place, that is the case due to FDM printing being able to print the entire product at once, meaning that there isn't any reason for the product to be manufactured using multiple manufacturing companies or technologies. However, the same can't be said about bubble-form moulding, and that is due to the probability of the mould used for the socket being made by a different manufacturer, using a different technology, and for it to then be transported somewhere else for the actual moulding process of the prosthetic.

Safe practices

When handling or working with an FDM 3d printer, multiple safety percussions should be taken to avoid any potential harm that could be inflicted upon the user. The first safety issue when it comes to FDM printers is heating, and the is because the printer functions by melting the plastics, and said plastics could have melting points of up to 250 degrees Celsius or even more. The main areas that should be avoided due to heat when working with an FDM printer are the nozzle and the bed. The nozzle is the location that the molten plastic would be extruded from, and obviously, due to that, it would be extremely hot and could easily burn the skin, and as such, it should not be touched whatsoever until it has cooled down. The second area to which heat could be applied during the printing process is the bed. As mentioned earlier, heat is also applied to the bed to prevent certain plastics from warping, although the bed would not be as hot as the nozzle, it could still go up to 100 degrees or over, and thus it should still be avoided by touch until it is made clear that its temperature has dropped. A way of checking the temperature of the nozzle and bed is by checking the printer's display screen for their temperature prior to touching the nozzle or bed, as well as that, nowadays, many FDM printers come with an enclosure to prevent the user from accidentally touching the nozzle or bed (19).

As mentioned, FDM printing functions by melting polymers, and because of the melting process, a lot of fumes from said polymers would be produced, and due to plastics being made up of crude oil, if those fumes were to be inhaled, they would be extremely harmful and dangerous to humans and can cause severe health issues such as heart diseases, asthma, damages to the nervous system, and more. Although this issue isn't major when working with plastics like ABS or PLA, it could be working with more toxic polymers. The best method to prevent fumes from being inhaled is to have the printer situated in a heavily ventilated area and to have respiratory masks be mandatory for daily personal protective equipment when working with extremely toxic plastics.

Additional comparison points

Ease of use

Due to FDM printers only requiring a 3D digital model for them to then automate the entire manufacturing process of the product, this leads to the technology being easy to use. Not only is that but the knowledge for all components of the printer and how they work is easily available on the internet, with numerous articles and videos of everything that the user would have to know, and said knowledge is also easily implemented as it doesn't require any prior knowledge. Of course, industrial FDM printers would require professional training, nonetheless, it is still relatively little and is way better than bubble-form moulding in terms of ease of use, that is the case for two main reasons, the production of the mould itself and the moulding processes. That is the case as although making moulds is generally easy if there is already an existing physical model of the product you want to mould, although in the case of prosthetic sockets, that isn't the case as each mould would have to be unique, and as such, the mould creating process would have to be done using subtractive manufacturing technologies which require a lot of prior knowledge and skill. When it comes to the bubble moulding process itself, although it's not necessarily difficult, it still requires more training compared to FDM printing.

Build volume & machine cost

When it comes to the built volume of FDM printing technologies, as mentioned earlier, desktop FDM printers it is small, however, industrial FDM printers do have very big build volumes allowing them to create much bigger products. Build volumes for industrial FDM printers can be around 600x400x600cm and up to 915x915x1000cm for The Terabot FDM printer (20) which is known for being one of the largest FDM printers currently on the market and is priced at around 35,000 USD (21). The mentioned sizes are more than to produce a prosthetic socket and thus removing any build volume issues. In terms of bubble-form moulding, the build volume isn't either a significant issue as the size of the product would only depend on the size of the polymer sheet that is being used, and when it comes to the size of the oven itself, that shouldn't be an issue for any industrial oven. When it comes to the price of the oven that is used for bubble-form moulding, it varies a lot, although for a good quality oven it would roughly be around 10,000 USD. (22)

Speed of production

One of the main drawbacks to FDM printing is how slow it is. If the product that is being printed is relatively big, at least when compared to the machine's build volume, it would take around a day or two for the product to be fully printed, and if extreme accuracy and good surface finish are required, it would take even longer than that as improving the accuracy of the print and the quality of the surface finish necessitates slowing down the rate at which the product is printed. Concerning bubble-form moulding, although the moulding process itself wouldn't take long and would only be a maximum of a couple of hours, the moulding process is what makes it a long and time-consuming method. That is the case as making a unique mould that is extremely accurate to the required dimensions is a very long process that could take weeks, if not months. That is the case because as mentioned earlier, prosthetic sockets require tailor-made moulds, and although making moulds of an existing physical model is easy and a relatively quick process, it takes very long to manufacture a unique, never seen before mould.

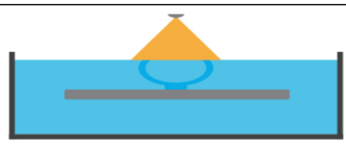
Stereolithography

How does SLA printing work?

Stereolithography or SLA printing is an AM technology that works by hardening liquid photopolymer resin. This process is done by pouring a liquid photopolymer resin material onto a resin tank/vat, using that, a building platform is coated with the material, the methods in which the building platform is coated differs from one type of SLA printer to another, said types would be discussed in the next section. After the building platform is coated, the curing process begins, and within it, a high intensity UV light that is shined upon the liquid material through the vat, the UV light traces the geometrical shape of the product by shining it onto two mirrors for it to then be redirected to the resin, the mirrors mentioned are known as galvos and are controlled using a galvanometer (23). Due to the unique properties of photopolymer materials, this creates cross-links between the photopolymer particles (oligomers), which causes the liquid material to harden and turn into a solid (24), following that, the surface of the print is once again coated and the process repeats until the full product has been fully printed.

Types of SLA printing machines (25)

Top-down



A top-down SLA printer is a printer in which the UV light source is placed at the top of the printer. The building platform is re-coated by lowering the building platform one layer height in it, then a build plate goes across the coating to smoothen it out.

Bottom-up

In this SLA machine type, the UV light source is placed under the vat and is shined onto it through a window, and the printing platform is placed on the top. The building platform is coated again as it gets lifted from the vat. Then a really slow peeling process is required to remove the cured material that got stuck onto the vat in the polymerization process.

CLIP

CLIP, also known as continues liquid interface production, is almost the same thing as a bottom-up SLA machine with the exception that the window between the UV light source and the vat is oxygen permeable, which prevents the resin from sticking onto the vat due to the oxygen layer over the window, bypassing the slow peeling process. The only issue with this type of machine is that currently it is very expensive.

Post-processing

Post-processing is a two stop process done after the product has been printed to ensure the best quality. The first step of post-processing a resin-based print is to submerge the print in clean isopropyl alcohol (IPA) for around 3 minutes and then rinsing it using a brush (26). This can be done manually or by the use of a post-washing machine that would do it automatically. This is done to help remove any excess uncured resin that could still be left on the surface of the print. The second step of post-processing a print is to post-cure it, this is done by applying heat and high intensity UV light to a finished SLA print. This is most commonly done using post-curing chambers and what happens is that heat is applied to the print to increase the mobility of polymer particles and then the UV light is applied to create extra cross-links between them that were not initially created in the printing process. What this done is that it maximizes the mechanical and chemical attributed of the material used for the print. This process usually takes around 5 minutes when using a UV chamber although it differs from one print to another depending on the thickness of the material. This process can also be done by placing the product under sunlight although it would take longer and would be less effective and climate condition reliant (27). There are also two in one post-processing chambers that can both wash and post-cure.

Post-processing chamber

Support structures

Support structures are necessary with SLA prints, and that is for the reason that if they're not placed, when the liquid resin is hardened, it would just float in the vat rather than sticking to the print. Just like with FDM, support structures are required for overhangs with an angle of over 45 degrees, except with bottom-up SLA printers needing supports for overhangs of over 19 degrees as the overhanging section could break in the peeling process. With SLA prints, the tips of the support structures are relatively small, meaning that they won't affect the surface quality much when they are removed, not only that but the already small damage that would be done by them could be entirely removed with proper finishing of the print's surface.

Material

What is it?

The material used for SLA printing is a liquid resin which is made up of photosensitive composition of oligomers, which are a molecules that are composed of repeating monomer (a molecule that forms a polymer chain if it reacts to another monomer), photosensitive meaning that it reacts with ultraviolet lights which is the way that SLA printers work and why these types of materials are the only ones that are compatible with SLA printing technologies.

Environmental compatibility

The liquid resin material used for SLA printing is not environmentally friendly and is extremely toxic to the environment and also to the user. Although, everything that was mentioned is when the material is still in its liquid form. When the material is cured/hardened it is considerably less toxic due to the fact that it can no longer penetrate the human skin. In spite of that, the material should still not be used for any food related applications or used in anything that could harm nearby creatures such as aquarium decoration unless the print has been sufficiently post-processed and the user has made sure that no pieces, or layers could be broken or scratched off, which is hard to guarantee so it's best to avoid using SLA prints for said applications.

Most used types of resins in SLA printing (28)

Standard resin	*Standard, or general purpose resin is the most used type of resin and is mostly utilized to make figurines and miniatures due to it having really smooth surface finish. The issue with using standard resin though is the fact that it is brittle making it unviable for tension sustaining products and mechanical applications.*	
Dental resin	*Dental resin, as the name applies is used for dental applications. It is mostly used for the manufacturing of removable retainers, that is due to them being biocompatible, meaning that even though the product is placed in the user's mouth, the resin wouldn't harm them. This type of resin also has extremely good tensile strength, and this it wouldn't fracture easily. The major drawbacks to this type of resin though is that it is extremely expensive.*	
Flexible resin	*Flexible resin is a resin material that is meant to replicate rubber. It is used in many applications such as prototyping and in some cases making impact dampening products, it is also used to make custom products such as bike grips. The key disadvantages to flexible resins though is that it has lower accuracy when printing compared to other resins, causing products to be more likely slightly smaller or bigger than intended.*	
Tough resin	*Tough resin is a durable and resilient type of resin that is widely used for prototyping parts that are later going to be made out of polypropylene and in some cases it can also be used as the main material and replace ABS for finished products. The major drawback to tough resin is that it has bad thermal resistance making it not suitable for applications that work with high temperatures.*	

SLA printing characteristics

Post-curing	Surface quality	Accuracy	Photopolymers only
One of the main points with SLA printing or resin-based printing in general is the ability to enhance the print's material physical and chemical properties which in some products might be a necessity. Said enhancement is done by applying more UV light radiation to it by using a post-curing chamber or sun light to form more polymer cross-links after the initial printing process has concluded.	*One of the most notable things about resin-based prints is their extremely smooth surface finish, to the point that with enough sanding you could get a resin-based print to be as smooth as glass. That is an important point since one of the main drawbacks to AM in general is the surface quality, this quality contradicts that, thus making them ideal for miniatures and figurines.*	*Another really important point about SLA printing is that it is especially accurate and has an impressive tolerance of ±0.01mm, leading to prints being very dimensionally accurate, which also allows for extremely detailed prints to be printed and still remain prominently precise and accurate to the 3D digital model.*	*A major characteristic to SLA printing is the fact that it is limited to photopolymer resin only and lacks the diversity of materials that other AM technologies such as FDM printing possess. Thus SLA printing is impractical for many products due to the main material it uses not having the properties that said products might be in need of.*

Strengths and weaknesses

Strengths	*As mentioned above, the main strengths of SLA printing is that it has amazing geometrical accuracy and generally produces prints with highly smooth surface finish making this type of technology ideal for miniatures and figurines. SLA printing also significantly less damaged with support structure compared to other technologies due to the tips being small.*
Weaknesses	*Main weaknesses of SLA printing compared to other manufacturing technologies is that it generally has a smaller build size. The material selection of SLA printing material is also very limited both in material types and color selection. Most materials are also brittle and toxic, making them unsuitable for mechanical, food, and animal housing applications, furthermore, resin from finished prints can't be melted and re-used. The post-washing process could also be an annoyance to many people and it would also increase the price of production using SLA.*

Applications of SLA printing

Desktop/Personal

Personal, or also known as desktop SLA printers (image shown on the left) are used for simple prototyping but is more commonly used as a household machine for random miniatures and figures, this is the case due to them being relatively cheap, not requiring much room space, and also the general design of desktop printers looking modern and stylish making them ideal, practical and fashionable office set-up addition for most people that are interested in 3D printing and also interested in owning one.

Industrial

Industrially, SLA printers are used for quickly manufacturing of detailed and intricate models of products, rapid prototyping, and as of recently, they have also been getting used a lot for dental applications such as the manufacturing of dentures and surgical guides. Industrial SLA printers do have a relatively big build volume however that comes at the cost of a huge increase in machine's price.

Product justification – SLA

Brief

SLA printing would be an ideal choice for the production of chess pieces since it would be able to provide hand-made like quality but would be able to provide it way faster than the traditional way. With the use of SLA printing, the designer would also be able to experiment with more unique and complex piece designs and geometries. SLA printing would also be able to surpass manufacturing processes used to make plastic chess pieces like injection moulding in terms of details, quality, and more qualities which would be talked through in this page that would justify the use of SLA over traditional manufacturing methods of chess pieces.

Complexity

In terms of complexity, SLA printing is superior to both injection moulding and hand-making/subtractive manufacturing. When it comes to injection moulding, making complex and unique chess pieces would be very expensive due to the mould-making process of said unique products being expensive and also very time consuming. In terms of subtractive manufacturing there are many complexity barriers that would prevent this method of being practically utilized in the manufacturing of complex chess pieces, said barriers would be things like undercuts, cavities, inner features, and also very smooth and round curves. Due to said issues with both injection moulding and also subtractive manufacturing this makes SLA printing better in terms of the production of more unique chess piece designs that would be more eye-catching and interesting to the consumer. Support material would also not be an issue because as mentioned earlier, the tips of the supports are small and would do relatively little damage that would anyways be removed during the finishing step.

Waste

Both injection moulding and also subtractive manufacturing produce waste in some form that make it so they're worse in term of waste-efficiency compared to SLA printing. For injection moulding, waste is produced in the form of flashing. Flashing is when excess molten plastic is poured into the mould, thus producing the product with excess plastic on it which would have to be later on removed. Excess plastic produced from flashing can be taken off of the product and then recycled for later use (29). SLA printing is not as good as injection moulding when it comes to waste efficiency and that's due to photopolymer resin being a thermoset, meaning that it can't be melted down and reformed. With regard to subtractive manufacturing, waste is an even bigger problem due to the amount of wasted material being produced from the cutting process of the material to get the required shape of the chess piece.

Accuracy and tolerance

In terms of accuracy and precision, both SLA printing and injection moulding are really good, as industrial SLA printing has a tolerance of around 0.01mm, and injection moulding comes in at 0.127mm (30). So although SLA printing is way better, such accuracy would not be demanded when it comes to the manufacturing of chess pieces. Regarding hand-making though, a lot of human error could occur during the production process which would not only lead to the waste of material due to it having to be thrown out as the size would be of acceptable range, but it would also lead to a big waste in time as the entire production process would have to be re-done for that piece. Although in the hands of professional carpenters really accurate and detailed chess pieces could be made.

Post-processing

Surface finish

Both injection moulding and SLA printing produce extremely good surface quality products from the manufacturing process without the need of much post-processing. Injection moulding would also be able to produce more glossy products, although after sanding, SLA technology prints could get an extremely smooth surface finish that would exceed injection moulding. In terms of hand-making, the finishing process is extremely time consuming, nonetheless, as mentioned in the accuracy section, in the hands of experienced and knowledgeable carpenters, exceptionally good surface finishes could be produced.

Post- curing

Due to the properties required for chess pieces, post-curing would not be necessary, although it might still be beneficial to do since it would improve on the print's material by enchasing its properties, thus increasing the strength, durability, and also the life-span of the pieces. Also, most industrial SLA printers come with a post-curing station built into them, meaning that machine space wouldn't need to be added for curing stations (27).

Materials

The material that would be used to produce chess pieces using SLA printing would be standard resin, this is the case since it is cheap, and provides a really good surface finish that chess pieces would require. Not only that but also special use resins such as dental or flexible resins aren't really necessary and using them would not benefit the product in any major way.

Capacity

Although desktop SLA printers have relatively small build size, industrial printers build size capacity increases a lot, thus allowing the manufacturer to produce multiple chess sets in one print cycle. But as mentioned previously, said increase in size does come at a significant increase in the machine's price tag which can be around to 7,000 USD or higher (31).

Sustainability – SLA

Recyclability

Unfortunately, one of the main drawbacks to SLA printing is the recyclability of resin, which is the main – and only – material that the printing technology functions with. That is the case due to photopolymer resin being a thermosetting polymer, meaning that if resin were to be heated, the polymer chains would begin to break apart and disintegrate, and as a result, it would cause the material to burn. Thus, unlike thermoplastic filament, photopolymer resin cannot be melted down and turned back to a liquid after the material has been cured. Additionally, in the case that a failed print does occur, the material cannot just simply be disposed of immediately, but rather it would have to be fully post-processed as it would be too harmful to the environment if the print were to be disposed of while still having small remains of liquid resin on the surface. Also, the remaining liquid resin that is left on the vat tank after a print cannot be re-used and should be disposed of by giving it to a recycling facility (26), that is the case because if that resin were to be put back into the initial resin container, contamination of the resin currently occupying the container could occur as the resin in the vat tank could have small bits of cured resin within it, that could interfere with the function of the uncured resin.

When it comes to injection moulding, recyclability is fully dependent on the material and not the technology itself since, unlike SLA printing, injection moulding is not limited to thermosetting polymers such as photopolymer resin. Also, any of the excess material that get accidentally injected into the mould can be removed and recycled for later use. When compared to hand-making, recyclability isn't very good, as any pieces of timber that would be shaved off would be extremely hard to clean and pile up for recycling purposes.

Waste

SLA printing has extremely good waste efficiency. That is the case as the same things that were mentioned for FDM printing in the FDM sustainability section could be applied for SLA printing as well, nevertheless, SLA printing is a bit better since the support structures used for SLA printing are more spaced out and are generally thinner than the ones used in FDM printing, meaning that the SLA printing produces even less waste from support structures when compared to FDM printing. As mentioned above, if any resin were to be left on the vat tank after a print, unfortunately, that resin would have to be appropriately disposed of to avoid contaminating the unused resin. Injection moulding is also very waste-efficient, as mentioned before, the only waste that injection moulding produces is from the excess material that might get poured into the mould, and even so, that material can just be removed and recycled for later use. However, in terms of hand-making, which is the other method used for the production of chess pieces, a lot of waste would be produced from the small pieces of wood that would be shaved off of the timber.

Localization

Although the market for SLA printing here in Oman is smaller than that of FDM printers, they are still readily available. In terms of resin, it is largely available and in wide varieties, even specialty resins such as dental or castable resin can be found at certain big 3D printing companies such as atoms lab. When it comes to the printers themselves, they're available, however, not many different types of printers can be found, spare parts could be an annoyance to get locally, and industrial printers are very rare to find, thus, if the manufacturer is looking for something specific, they might have to import it from somewhere, most likely the UAE as the market for SLA printing there is much bigger, and as touched upon earlier in the report, the transportation fees and time is very little from Oman to the UAE, meaning that it wouldn't be a major issue. Just like mentioned in the FDM printing sustainability section, SLA printing is also easily done in one place and that is due to the technology being able to print the entire product at once in one location without the need for other technologies. Regarding the post-washing and curing steps, many industrial printers have post-curing chambers built in them, meaning that even the post-curing step can be done in one place. Although, for the post-washing step, a separate machine would have to be installed.

When it comes to injection moulding, it is extremely rare and hard to find both machines and parts here in Oman and also nearby countries, meaning that machine parts would have to be imported for the machine to be made here, said import fees would most likely be extremely expensive due to them having to be transported by air and for far distances. And in the case that the machine fails, an inspector would have to be flown from another country to check on and fix the machine which would cost both a lot of money and time.

Energy

SLA printing technologies are extremely energy-efficient, even more so than FDM printers, as they consume around 40 watts of electricity only compared to FDM's 50watts per hour, and that is the case since they only use one motor, which is the galvanometer, and other than that, the most energy-consuming components used in them would be the LED array and the LCD screens that might be on the printer (32). When compared to injection moulding, SLA printing proves to be particularly better, and that is attributed to the extremely high energy consumption of injection moulding. A study shows that on average, injection moulding consumes around 1.47kWh/kg (33), although the plastics used to carry out said study were polymers that melt at temperatures of around 200 degrees Celsius while the plastic most commonly used for the manufacturing of chess pieces is polymethyl methacrylate, which has a melting point of around 160 degree Celsius (34), and as such, the energy consumption when manufacturing chess pieces might be a bit less than the given 1.47kWh/kg, nonetheless, it would still be extremely high especially when compared to SLA printing technologies.

Safe practices

When compared to FDM, SLA printing, in general, is considerably more dangerous and as a result, more safety percussions are necessary to be taken to ensure a safe work environment for the user. The first safety measure that isn't necessary nevertheless, it is still important, is to keep the printer in a well-ventilated area, that is because when uncured resin is exposed and is open to the air, nanoscale particles could be given off, and although the particles given off by uncured resin are in very tiny amounts and are way less harmful than the potential intake of harmful gases produced by FDM printing, nonetheless, if they're inhaled at a daily bases, they could lead to severe health issues. As well as that, if the user has had any previous respiratory medical issues, it is recommended that they wear a respirator mask whenever they are handling uncured resin.

A really important point when it comes to SLA printing is how the user safely handles and post-processes prints, for any prints that haven't been washed via a solvent could still contain remains of uncured resin on their surface, which could be harmful as said uncured resin could penetrate the skin and cause a rash known as contact dermatitis. Firstly, during any occasion that the user handles uncured resin, they must always wear nitrile gloves, and in the case that resin does spill on the gloves, they should be thrown out and replaced. To handle un-washed resin prints properly, the user must firstly fill any container big enough to fully place the print in with at least 70% isopropyl alcohol (IPA), although 99% isopropyl alcohol is recommended. Following that, the print should be placed into the filled container and then slowly shaken around in the container and scrubbed using a toothbrush to be able to get rid of any major accumulation of resin on the surface. From there on, it is recommended to post-cure the print just in case any remains of the uncured resin are still on the surface. When it comes to the disposal of the IPA used to wash the print, it should never be poured into government sewer systems such as drains, nor should it be simply thrown into the trash bin as the IPA would be contaminated with the uncured resin, what should be done is either the IPA is given to an appropriate facility to deal with or it could also be left out in the sun to evaporate, it should also be noted that the container used to wash the print should never be reused for any other purposes other than washing prints as it would not be safe for use anymore. Also, as mentioned earlier, in the case the failed prints occur, they should be either post-processed first and then thrown out or given to appropriate facilities to deal with them. In the occurrence that uncured resin does come in contact with the skin, the user should promptly clean the affected area with the use of soap and water for at least five minutes. Moreover, if resin is also spilt on any garment, said garment should be washed thoroughly before being worn again. (26)

Additional comparison points

Ease of use

Although SLA printing is similar to FDM printing in that the manufacturing process itself is fully automated, SLA does require significantly more training, and that is due to the bigger amount of knowledge about the printer that the user has to know, and also because of the significantly larger amount of safety precautions that the user has to take in order to safely perform a print. However, just like with FDM printing, all of the info required for operating an SLA printer is available on the internet. In comparison, injection moulding requires professional training for a couple of weeks until someone is deemed qualified for operating the machine, thus consequently, it is a more expensive process to train injection moulding operators compared to SLA. When it comes to hand-making, making dimensionally accurate and stunning detail, especially on a small product like a chess piece, requires years of training and knowledge, which also results in more costly staff expenses.

Build volume & machine cost

When it comes to the build volume of SLA printing technologies, as mentioned earlier, desktop printers are small and don't have enough capacity for the manufacturing of many items at once, although industrial do have big enough built capacity to manufacture multiple chess sets in one print cycle. One of the biggest SLA printer currently on the market, the Phenom XXL, has a build volume of 52.7x28x55cm (, and is priced at around 7,000 USD (31, 35). And overall, industrial SLA printers can be as cheap as 3,000 USD to printers that can be up to 500,000 USD for printers with extreme detail and large build volumes (36). With regards to injection moulding, machines generally have a very big build capacity which could also be able to produce many chess pieces during one cycle of the machine. On average, the price of industrial injection moulding machines ranges from 50,000 to 200,000 USD, which is way more expensive when compared to the starting price of industrial SLA printers.

Speed of production

Just like FDM technologies, SLA printing suffers from its rate of production and is generally even slower than FDM printing, and just like with FDM printing, if more detail is require for the product, then the printing rate would be even slower. This is a major disadvantage especially when compared to injection moulding's extremely face rate of production, as injection moulding can produce plastic products in around 30 seconds, and probably nothing more than 2 minutes depending on plastic being used and the size of product (37). When it comes to hand-making, specifically when talking about quality products that require extremely good geometrical accuracy, the process can be very lengthy and time consuming, and if any failed products do occur, the entire process would have to be redone which would consequently lead to even more time being used.

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