Additive Manufacturing In Watch Industry

Article · October 2022

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2020-2021 Academic Year

Additive Manufacturing in the watch industry

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Abstract

Additive manufacturing in the watch industry is an interesting development in the branch of technological processes. This paper has the purpose to describe all of them, for instance we can refer to the freedom in creating the watch case, the good roughness reached by certain process (i.e. we have founded that for BJ of stainless steel we can reach 6.3 ± 0.4 μm without post-processing, and 0.88 ± 0.45 μm with it [85]), reduction of the cots, due to the fact that we doesn’t use tools or mould and many others. Although some problems still to be overcome, more study must be done in order to expand the choice of materials that can be printed. More insights have to be done on the pieces of the watch that we can produce; for instance, Barrelhand produce the first 3D print movement.

Introduction

Watch industry is a sector that have a strong connection with its heritage and traditional handmade manufacturing. A classic watch is composed on the outside by: case, bezel, dial, hands, crystal, crown, lug, strap, buckle Figure 1, on the inside it is present the mechanism that could be a mechanical or quartz movement.

Figure 1 Watch components [55]

The case contains the movement mechanism and the lugs (the parts where the strap connect to the case), can be done in different materials: metallic, ceramic or plastic; with different finishing process that create a shiny or matte surface either by additional manufacturing or traditional techniques.

The crown is used for setting the time, in some cases can do also other adjustment like the date for instance.

The strap secures the watch to your wrist, it could be done in a wide range of materials: leather, fabric, metal, nylon, rubber; we found some examples of bracelets manufactured via AM made of metal and nylon.

The dial is the main part of a watch, it could be done in different colours and textures, thanks to the different combination of material and process (AM or traditional) that can be used for this part. On top of the watch face the hands indicate the time, more information can be read by looking at additional hands. The crystal, that can also be made of plastic, protect the dial from dust and dirt, we found a company that during prototyping manage to 3D print the crystal [55].

This paper aims to present the achievement done by additive manufacturing process in the watchmaking field. We talked about the main techniques that are now present on the market as a consolidate process, as well as some future improvements in order to better optimize the process.

One of the most important challenge is to combine the machine to the worked material, by choosing the most suitable process parameter, for obtain a high-quality part as expected by these products. In fact, for such a recent technology we do not have the high amount of data that exist for traditional process and perform experimental studies could be extremely expansive taken in account the precious material used for these applications.

We started with a brief explanation of the main additive manufacturing processes and materials used in this field. In the materials section we present the advantages of realizing a part in a specific material by AM techniques, highlighting the increasing of mechanical properties and the cost/waste reduction: Material Extrusion, Selective Laser Melting (SLM), Selective Sintering (SLS), Stereolithography (SLA) and Binder Jetting (BJ). There are also some limitations, up to now, mostly regarding how the variation of process parameters can affect the final components. We have than write about the main applications available on the market as well as some early production examples. In this part we connect the watch's part with the process and its material. Since some parts are made with ceramic materials, we also talked about application made with ceramic injection moulding, for have a better comparison with the current state of the art in this sector.

Moreover, we have made a comparison between additive manufacturing and the traditional process. In this section we discuss about the pros of this new technology, such as the possibility to create complex and different shape quickly, without invest lot of money in different machines, the best application for the prototyping step, the advantages given in term of mechanical properties increasing thanks to localized heat treatment, that can occur during some processes due to the high cooling rate. We have also added a comparison of the surface's roughness achieved by singles process and how these technologies impact on the environment. In the end we summarized our work by highlight the main important achievement and current limitation of additive manufacturing in the watch industry, some future improvements are also reported.

1. Additive Manufacturing technologies in the watch industry

Introduction

In the following chapter there will be analysed some of the AM technologies that are used in the watch field. The following contents aim to show how these technologies works to better understand the main process that is applied for the manufacturing of the watches. We have analysed the processes of Material Extrusion, Selective Laser Sintering (SLS) and Stereolithography (SLA) which regarding the production of plastic and polymer watches. And finally, we have decided to describe the processes of Laser Melting and Binder Jetting that are the main processes that are used for the manufacturing of the metal watches. The following Table 1 shows the classification of the AM technologies that we have been analysed [73].

Table 1: Classification of the AM technologies [73][88]

Process categories	**Definition**	**Technology**	**Materials**
Binder Jetting	Liquid bonding agent is selectively deposited to join powder materials	3D printing	Metal Polymer Ceramic
Material Extrusion	Material is selectively dispensed trough a nozzle or orifice	Fused Deposition Modelling	Polymer
Powder bed fusion	Thermal energy selectively fuses regions of a powder bed	Selective Laser Sintering Selective Laser Melting	Metal Polymer Ceramic
Vat photopolymerization	Liquid photopolymer in a vat is selectively cured by light-activated polymerization	Stereolithography	Photopolymer Ceramic

1.1.Material Extrusion

All versions of the material extrusion process consist of five steps: material loading, liquification, extrusion, solidification, and bonding.

In the material extrusion systems, there is a chamber from which the material is extruded. Most bulk material is supplied as a solid and the most suitable methods of supply are in pellet or powder form. In other case the material is fed in as a continuous filament, as Figure 2 shows. The chamber itself is the main location for the liquification process. Pellets, granules, or powders are fed through the chamber under gravity or with the aid of a screw. Materials that are fed through the system under gravity require a plunger or compressed gas to force it through the narrow nozzle. Screw feeding pushes the material through to the base of the reservoir and it can be sufficient to generate the pressure needed to push it through the nozzle as well. A continuous filament can be pushed into the reservoir chamber, thus providing a mechanism for generating an input pressure for the nozzle [5].

What is held in the chamber will become a liquid that can be pushed through the die or nozzle. Such heat is applied by heater coils wrapped around the chamber and ideally this heat is applied to maintain a constant temperature in the melt. The material inside the chamber should be kept in a molten state but care should be taken to maintain it at as low a temperature as possible since some polymers degrade quickly at higher temperatures and could also burn, leaving residue on the inside of the chamber that would be difficult to remove and that would contaminate the melt. A higher temperature inside the chamber also requires additional cooling following extrusion [5].

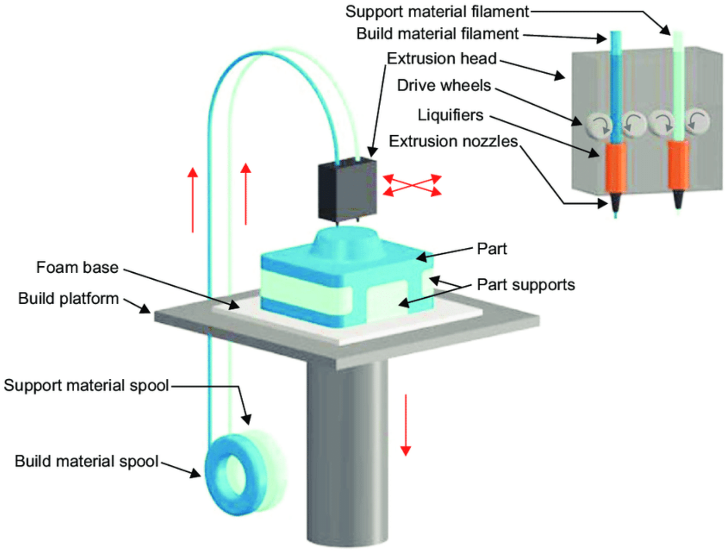


Figure 2: Schematic of Material Extrusion systems [19]

The most common material extrusion technology is Fused Deposition Modelling (FDM). FDM uses a heating chamber to liquefy polymer that is fed into the system as a filament. The filament is pushed into the chamber by a traction wheel arrangement and this pushing generates the extrusion pressure. A typical FDM machine can be seen in Figure 3.

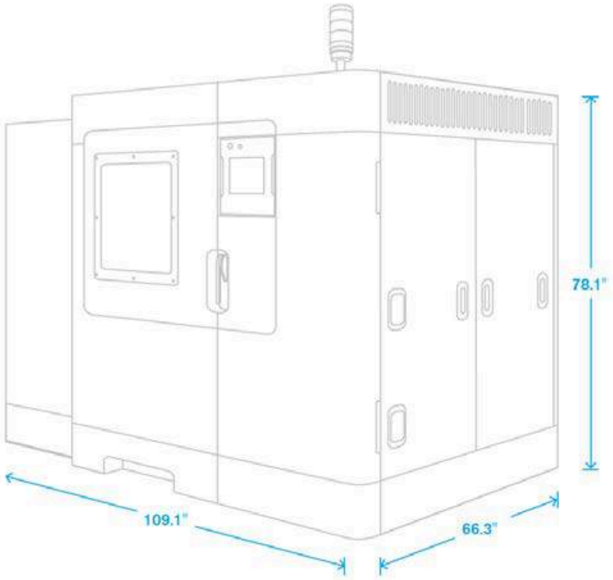


Figure 3: FDM machine: Stratasys F900 [20]

The major strength of FDM is in the range of materials and the effective mechanical properties of resulting parts made using this technology. Parts made using FDM are among the strongest for any polymer-based additive manufacturing process. The main drawback to using this technology is the build speed. The inertia of the plotting heads means that the maximum speeds and accelerations that can be obtained are somewhat smaller than other systems; furthermore, FDM requires material to be plotted in a point-wise, vector fashion that involves many changes in direction. The most popular material is the ABS material, which can be used on all current FDM machines [5].

1.2. Selective Laser Melting (SLM)

Selective Laser Melting (SLM) is a new additive technology in which Laser is used for heat source, Selective means that all powders are not processed by laser simultaneously, but powders are processed selectively when and where it is required. While Melting implies that all powders are completely melted.[57]

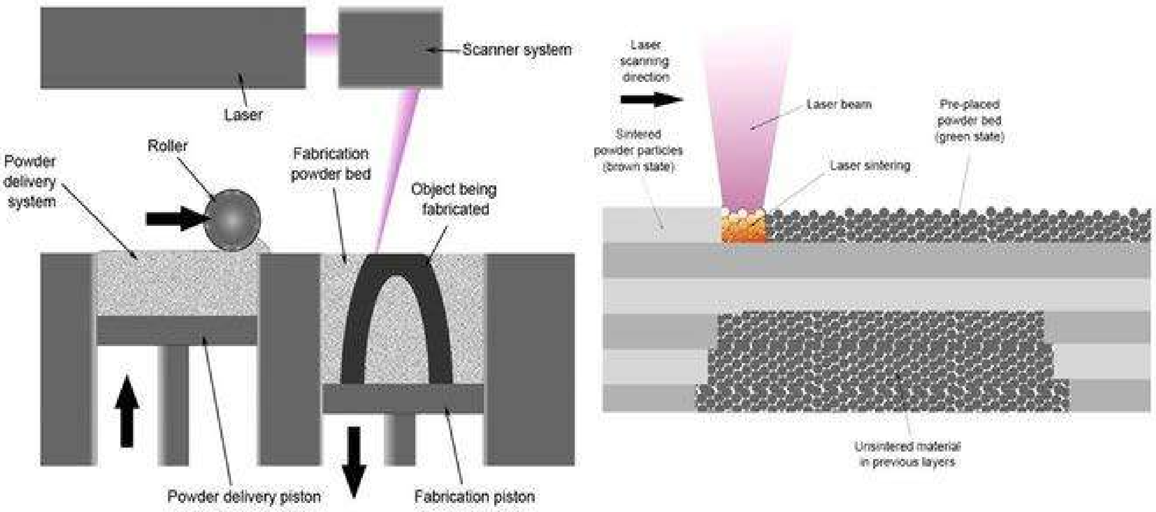


Figure 4: Working of SLM Process[58]

Description of Process

The aim is to make a layer of predefined geometry with CAD by sequence of 1) a substrate is lowered down to a depth equal to layer thickness, 2) a powder layer is spread on the substrate, and 3) the deposited powder layer is scanned by the laser beam to fuse at the selected area. Before printing, the whole build chamber is flooded with inert gas (argon/nitrogen) to minimize oxidation at high temperatures. The sequence is repeated until the final product is complete. Initially powder is taken out from powder container and poured on substrate, substrate is placed over piston for vertical movement needs. Scanner system is used to scan the deposited layer on substrate using laser beam. Powder delivery system piston moves upward, and fabrication piston moves downward so to powder placed on substrate with the help of roller, laser beam melts and fuses in desired shape over a layer and this carried out for each layer by layer until the work is fabricated.

Powder

The powder that can be used are metal, ceramic and polymer. Powder bed density is preferred for this, shape is taken as spherical and, in this case, when they are tightly fixed there remains a gap. In order to fill this gap, another small powder is needed known as bimodal distribution increasing total density, but still remains a small gap at intersecting space of one small and two big powders. For filling it another smaller powder is taken in account increasing powder bed density again in trimodal distribution.
Since our application is oriented with watch so powders which can be used for that are Titanium with mesh size 150 and purity of 99.9%. Silver 99.9% pure with atomized water, next is 18k Gold which is a composition of mainly gold silver and copper based on need with 10 µm size.[61]

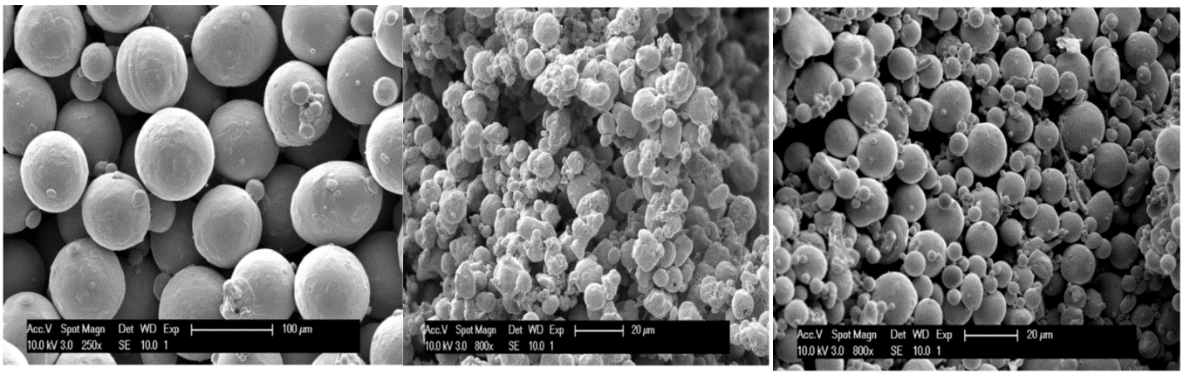


Figure 5: At the left titanium powder. At the center silver powder. At the right 18K gold powder[61]

Laser

SLM machines are equipped with from 50 to 500 W of power while ceramic need 500 W, Polymers needs 5 W. As the melt pool width laser power can be automatically changed. CO_2, Nd:YAG and fiber lasers are used with the wavelengths 10.6 µm, 1.06 and 1.08 µm respectively. Small wavelengths absorbed by metals and their alloys so metals and ceramic (carbides) use Nd:YAG while ceramic (oxides) absorbs CO_2. Laser beam diameter varies from 30 to 600 µm [59]. Laser beam used both in continuous and pulse mode. In pulse mode its peak power is higher than average power. These pulses used for milliseconds and higher peak power allows to process higher melting point materials. This not only melts the powder but also creates plasma. This plasma gives rise to recoil pressure resulting in flattening of melt pool and reducing porosity and increasing surface smoothness.
As powders are fully melted, they go for fast solidification which leads to shrinkage because there is porosity and this all generates residual stresses. To remove them we can do annealing

1.3. Selective Sintering (SLS)

Selective laser Sintering (SLS) is a technology that uses laser as the source for sintering the powder into a single part in a layer-by-layer process. Sintering/melting (SLS/SLM) are the same process. Figure 6 represents the layout of SLS using CO2 laser. The process is done in a confined area as the laser is the source of the binding the light rays are not allowed into the chamber when printing. The powder is filled in the vat for layer spreading. The process begins with the layer sintering of the powder spread over the platform initially. Then the platform moves in the z axis and the powder is spread over the next layer for further sintering. The process continues till the object is completed [10].

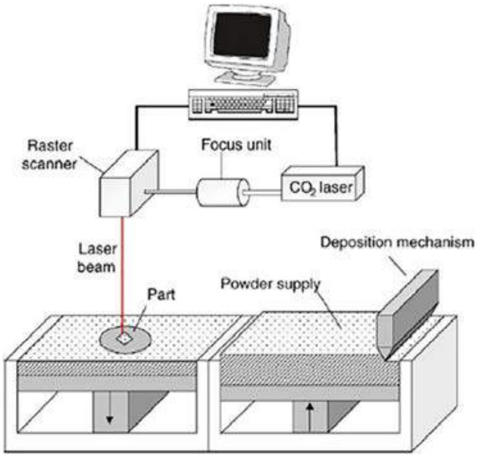


Figure 6: Schematic overview of SLS process [10]

1.4. Stereolithography (SLA)

Stereolithography more commonly known as SLA 3D printing is one of the most important additive manufacturing processes. It involves the curing or solidification of a liquid photosensitive polymer through the use of an irradiated light source, which supplies this energy that is needed to start a chemical reaction for bonding large numbers of small molecules and forming a highly cross-linked polymer.[63]

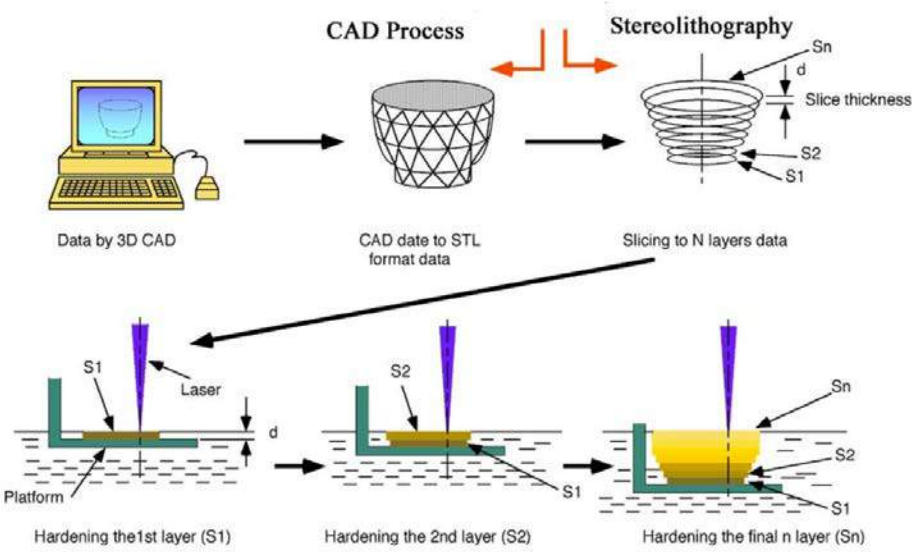


Figure 7 Process of Stereolithography [65]

Components that are used are resin tank which is filled with photopolymer this liquid resin is usually a clear liquid plastic. Movable build platform which is dipped in resin tank and can be move up and down based on need.

A highly powered UV laser hits and solidifies the liquid. This is done layer by layer until we reach the fabrication of part [64].

The resin selection as needed in watch manufacturing can be done with the help of process parameters needed by taking Table 2 as reference. After finishing the material polymerization, the build platform rises out of the tank and excess resin is drained out. Then model is removed from platform, excess resin is washed out, and then placed in UV oven for final curing. This post processing helps in improving the strength and gives stability to the fabricated part [64].

Table 2 Deciding parameters for selection of resins [67]

	Standard & Clear	Tough	Durable	Heat resistant	Ceramic reinforced
IZOD impact strength (J/m)	25	38	109	14	N/A
Elongation at break (%)	6.2	24	49	2	5.6
Tensile strength (Mpa)	65	55.7	31.8	51.1	75.2
Tensile Modulus (Gpa)	2.8	2.8	1.26	3.6	4.1
Flexural Modulus (Gpa)	2.2	1.6	0.82	3.3	3.7
HDT @ 0.45 Mpa (°C)	73	48	43	289	88

1.5. Binder Jetting

Binder jetting process normally uses two materials, namely the metal/ceramic-based material of which the part is to be made and a binder material, which glues the metal/ceramic powder material between and within the layers. The binder is usually a liquid and the metal/ceramic is in the form of a solid powder. The metal/ceramic is spread, and a layer of binder is deposited over the powder metal/ceramic layer, where required, which is dictated by the Computer Aided Design (CAD) model. This process is iterated for building the entire part (Figure 8). However, the BJ process involves several post-processes that follow the printing of the parts such as curing, de-powdering, sintering, infiltration, annealing, and finishing. These post-processes sometimes take longer time than the actual printing (especially the sintering of the parts) and may incur significant costs. One of the significant advantages of BJ is that the parts can be produced without support structures [11].

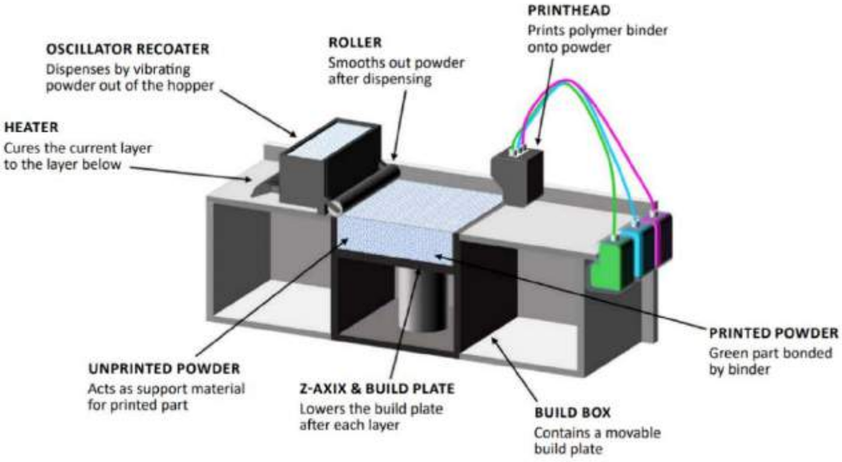


Figure 8: Binder Jetting technology [24]

The build parts lie on the loose powder bed, which is not bonded together. Hence, the entire build volume can be stacked with several parts with a gap of just few layers of distance between them. The printing process itself is faster than SLM process and can be accelerated by increasing the number of print head holes that deposit the material and the binder. It also allows a two-material approach, where different powder-binder combinations can lead to different mechanical properties, simply by changing the powder-binder ratio. Coarse powders can also be used in this process, which significantly cuts the cost of manufacturing very fine powders. As these methods do not involve heating during the building process, there are no residual stresses created in the parts, unlike in the SLM process, and BJ is regarded as one of the most cost-effective AM processes to build three-dimensional parts with added functionalities. Since there is no melting involved in the BJ process and the consolidation takes place predominantly by sintering, there is always a possibility for the presence of porosities, and the volume, size, and shape of the pores may differ within different parts produced in the same batch. Moreover, the parts are expected to have a coarse microstructure, since the parts have to undergo thermal treatments such as curing, sintering, and annealing once they are printed with the binder. Hence, the mechanical properties of binder jetting parts are not as strong as the parts produced by SLM [11].

2. Materials in the watch industry

Introduction

In this chapter we want to do an analysis of some of the most important materials that are used in watch industry, to underline what are their main characteristics, problems to manage them in additive manufacturing and what are the possible solutions. However more study must be done to expand the overall choice of materials and colours that can be selected from the costumer.
The materials that have been investigated are: Stainless steel, Titanium, Gold, Ceramic and Nylon.

Table 3 Comparison between the materials that have been study in this chapter

	Stainless Steel	Titanium	Gold	Ceramic	Nylon
Density	4	3	5	2-3	1
Cost of raw material	3	4	5	2	1
Corrosion resistant	4	5	4	-	-
Durability in time	4-5	4	3	5	1
Hypoallergenic	*	yes	*	yes	yes

*Most allergenic reactions are due to the presence of Nickel as an alloying element, so its reaction on the human body depends on that content.

2.1. Stainless Steel

Introduction

Stainless steel, more precisely austenitic stainless steel is one of the most used material in the watch industry. Thanks to the high corrosive resistance and the high hardness a stainless steel's surface maintains its beauty for a long time even in a non-ideal environment.
Stainless steel is 100% recyclable so we can use old parts to produce new ones that will be recycled once again at the end of their lifetime.
The most used stainless steels alloy in this field are: 304, 316L, 904L.

Table 4 steel composition AISI

	304		316L		904L	
	min	max	min	max	min	max
Ni	8%	10.50%	10%	14%	23%	28%
Cr	18%	20%	16%	18%	19%	23%
Mo	-	-	2%	3%	4%	5%
Cu	-	-	-	-	1%	2%
S		<0.03%		<0.03%		<0.035%
P		<0.045%		<0.045%		<0.045%
Si		<1%		<1%		<1%
Mn		<2%		<2%		<2%
C		<0.03%		<0.03%		<0.02%
Fe		BAL		BAL		BAL

The 304 is the cheapest one and is used in low end watches, the 316L better resist to corrosion because of molybdenum addition, both contain a lower percentage of Ni, they are used for preventing skin irritation that can occur in some people due to Ni intolerance. The 904L is the most expensive of the three, it has copper addition for increasing corrosion resistance but is also difficult to process.

Benefit of using AM

The most common method to process stainless steel through additive manufacturing is laser powder bed fusion [49].

With AM we can create the final piece layer by layer having more control on the microstructures, it is possible to have fast solidification rates and high thermal gradients. This allow us to increasing mechanical and corrosion properties that are not achievable with traditional process. In paper [50] AM 316L has been tested to wear resistance, results show a better wear resistance respect to a traditional manufactured part Figure 9, where COF stands for coefficient of friction.

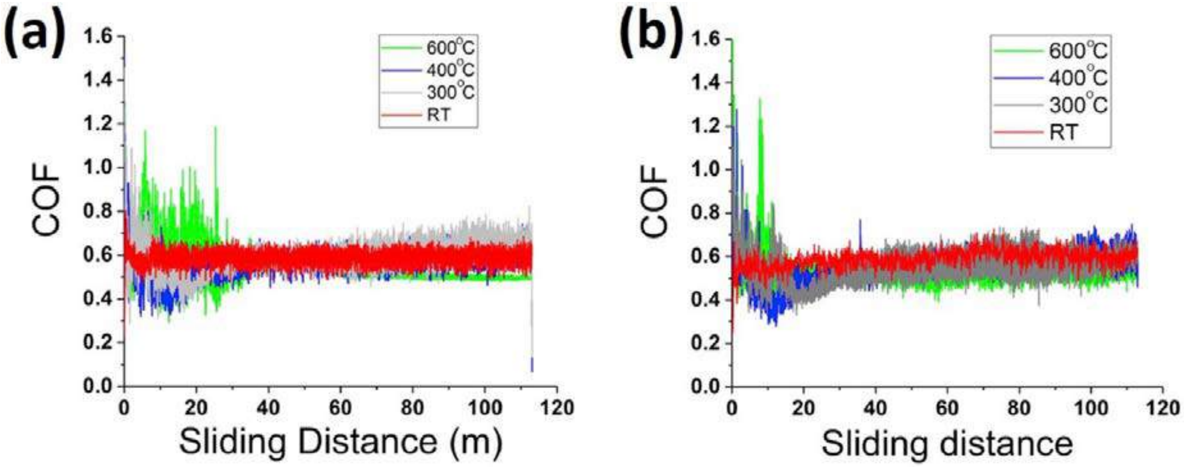


Figure 9 Friction vs sliding distance curves at different temperatures; a) SLM 316L SS @RT=25 steady state COF of 0.5, and b) conventional 316 SS @RT=25 steady state COF of 0.73 [50]

Some other studies resumed in paper [49] have reported that it is possible to obtain austenitic stainless steel with excellent pitting corrosion resistance thanks to the high solidification rate.

These two characteristics, wear resistance and pitting resistance, seems to give to the AM stainless steels high erosion-corrosion resistance. However, some other studies have shown an opposite behaviour; the process is still unclear.

These previously citated studies reported also other mechanical properties increasing with AM manufacturing that are not in our interest to talk about since they are not strictly related to watch parts.

Problems

The main problems with this kind of process are related to a non-homogeneous structure, this happens mostly because of wrong process parameter selection, and consist in: porosities, incomplete fusion holes, and cracks [51].

- Porosities: small typically spherical defect, because of the fast-cooling rate some gas particles cannot come out from the piece during the solidification process Figure 10.

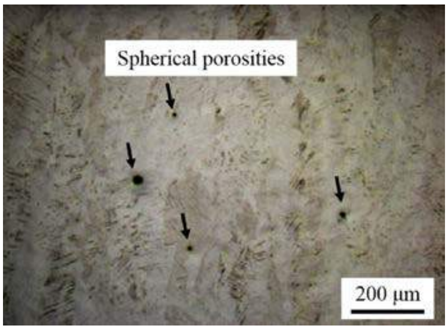


Figure 10 Optical image of spherical porosities (marked by arrows) in an SLM part [52]

- Incomplete fusion holes: also known as lack of fusion (LOF) due to a low energy input that is not able to fully melt the powder layer, this creates some un-melted powder particles trapped inside the material. It could be recovered by post processing treatment Figure 11.

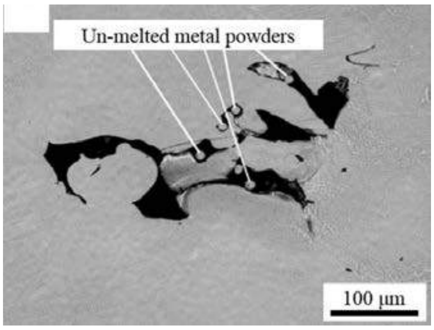


Figure 11 LOF defects with un-melted metal [52]

- Cracks: due to the large temperature gradient, between the spot affected by the laser and the other part that is not, it is generated a residual thermal stress that can cause crack initiation and propagation Figure 12.

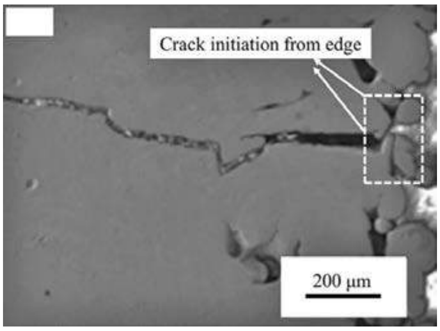


Figure 12 Crack morphology [52]

2.2. Titanium

Introduction

Titanium is used in watch industry mainly because of its property to be the most biocompatible metal (it is used in biomedical implants), it is also one of the most corrosive resistant common metal. Compared to steel is lighter (it is used in aerospace field) but it is also more expensive 4-5 times more than stainless steel and because of his lower hardness it is also easier to scratch. [52]

Benefit of using AM

Titanium parts are produced using a titanium hydride (TiH_2) powder for printing a green part that needs to be debinding, dehydrided and sintered. This powder, according to [52],[53] is the best compromise to achieve a low porosity green part while keeping the cost low. In fact, with this powder the main cost is the material one, that can be taken even from scrap, the hydrogenation process is relatively inexpensive thanks to ADMA Products, Inc. that developed new methods to make low-cost TiH_2 powder. Moreover, hydrogen helps to limit oxidation of powder during thermal process.

The “Solvent on Granules 3D-Printing” (SG-3DP) process developed at the University of Applied Sciences and Arts Western Switzerland, described in paper [54], was used for printing experimental watch cases with TiH_2 powder using a granule layer thickness of 100 µm.

For the watch case, Figure 13, the results where: 28% linear shrinkage compared with the printed green bodies, and 92% of theoretical density. The surface roughness (Ra) of as sintered parts is 4.5 ± 0.5 µm on the top face. Despite the high shrinkage, the sintered watch cases exhibit good shape preservation [54].

Figure 13 Part design (a), as-printed green part and Titanium watch case sintered at 1200 °C (b) [54]

The main benefit in processing Ti alloys with additive manufacturing is related to the fact that all the material that is bought is used without wasting it by chip formation. In paper [72] are summarized different studies done with Ti alloy all of them reported to obtain a 3D-printed part with mechanical properties similar to the traditional cast or wrought titanium alloy. Even though some studies show the increasing of a specific property by changing a specific process parameter, there are too many parameters in these process that have an unclear effect on the final results, more experiments have to be developed.

2.3.Gold

Introduction

Gold is the most desirable of metals, and it is the most common know of precious metal thanks to his unique characteristics. It is one of the oldest materials that have been used during the century to produce watches' part. Gold may be used to make watch cases, bezels, bracelets, and the most precious parts of the movement. Nowadays the movement of the parts cannot be produced by 3D printing, because we need a precision that isn't still reached with this type of technology, but it could be a future improvement.

Gold does not work by itself. Gold (chemical symbol Au) is the most malleable and ductile of all metals. Due to this we must mixed it with other metals to stronger it. The alloying elements that we add to it affects his colour: yellow, white or red/pink. We want to concentrate ourselves on the developing of Gold - 18kt (yellow gold), due to the fact that is the most common use for watches and jewelleries and the ones that has been made most research with additive manufacturing.

[33]Gold - 18kt:

- Gold (Au) - 75.1%
- Silver (Ag) - 12.4%
- Copper (Cu) - 12.5%

Problems

The production of gold parts with AM is thanks to selective laser melting technology (SLM), due to this we must consider some important problems that can the material have been affected. Using this technology, we need to melt the material, so we want that the heat produced by laser have been absorbed by the gold. The problem is that it is very difficult to process by laser melting because of his high reflectivity and thermal conductivity. Most of the laser energy is therefore reflected, the metal is difficult to melt despite its low melting temperature. The melt pool is very small and the process window for gold alloys is much narrower compared to steel or titanium alloys [33].

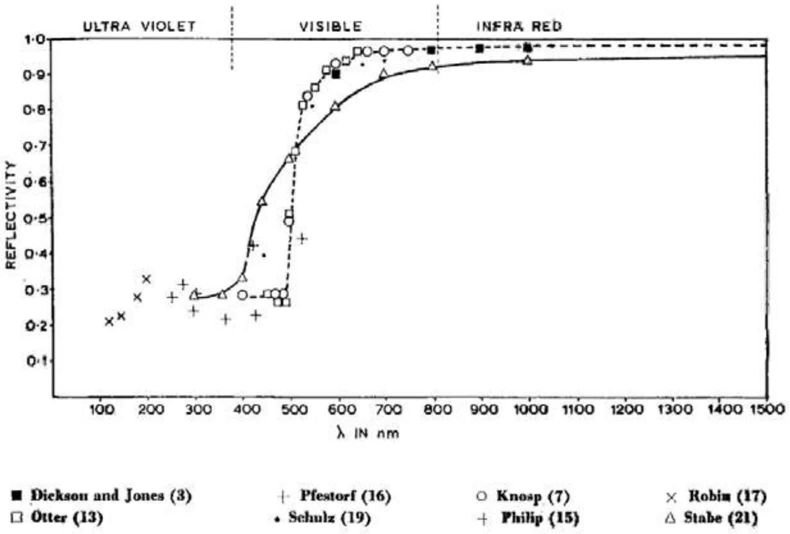


Figure 14 Reflectivity of gold in terms of the wavelength λ of light in nm. Combined results of several studies [41]

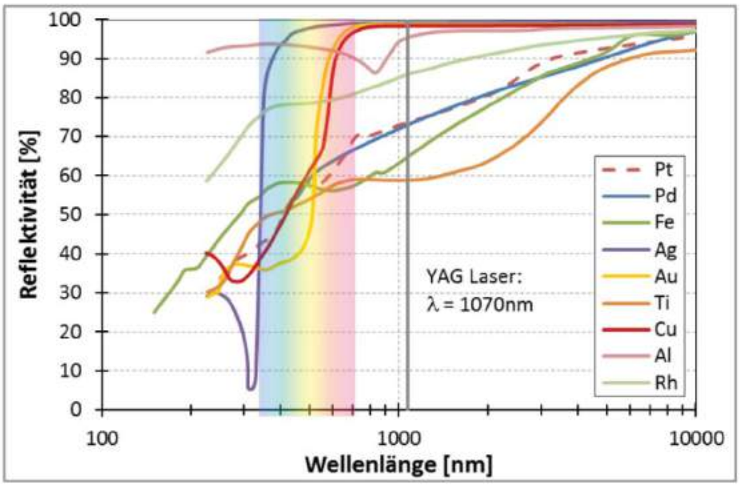
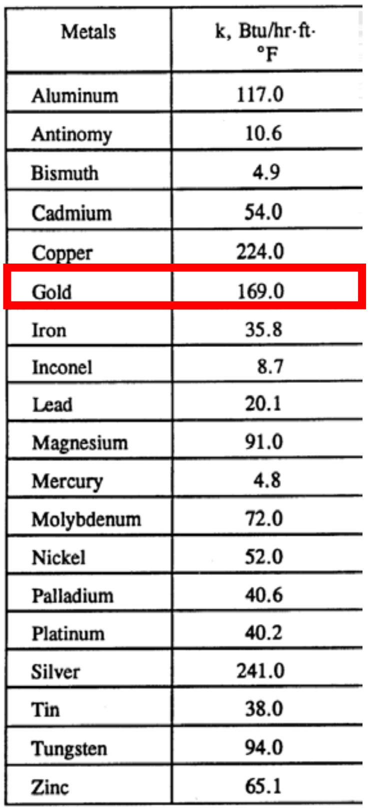


Figure 15 Reflectivity of some metals as a function of wavelength (x = wavelength and y = reflectivity). Pt = platinum, Pd = palladium, Fe = iron, Ag = silver, Au = gold, Ti = titanium, Cu = copper, Al = aluminium and Rh = rhodium [34]

The laser sources in selective laser melting machines are mostly Nd:YAG lasers with a wavelength of 1064nm (infrared wavelength) [34]. Due to this we can understand very well that the uses of this type of wavelength cause an increase of the reflectivity of the gold, and subsequentially a more difficulty to melt it.

Table 5 Metals - Thermal properties k,ρ,c,α (thermal conductivity k, mass density ρ, heat capacity c and thermal diffusivity α). 1 Watt = 3.4 Btu/h, 1 m = 3.28084 ft and $t_f[°F] = 1.8 \cdot (t_k[K] - 273.15) + 32$. [42]



Metals	k, Btu/hr·ft·°F
Aluminum	117.0
Antimony	10.6
Bismuth	4.9
Cadmium	54.0
Copper	224.0
Gold	169.0
Iron	35.8
Inconel	8.7
Lead	20.1
Magnesium	91.0
Mercury	4.8
Molybdenum	72.0
Nickel	52.0
Palladium	40.6
Platinum	40.2
Silver	241.0
Tin	38.0
Tungsten	94.0
Zinc	65.1

As we can see in the Table 5, gold is one of the metals that has the highest thermal conductivity, so we need to decrease it in order to avoid the rapid reduce of energy that has previously absorbed during the laser emission.

Solutions

Powder treatment

We have picked up results from a study taken by the article [34], that underline the fact that without a powder treatment the quality of the component that they have created was not acceptable, because the high level of porosity that still have been present in the material. Porosity is mainly affected by the reflectivity of the gold. In fact, if we consider for instance the hatch distance (distance between two parallel scan line), that is one of the two important parameters of the SLM (the other is the scan speed), the porosity is very high, because most of the laser energy is reflected from the already melted surface, as shown in [34].

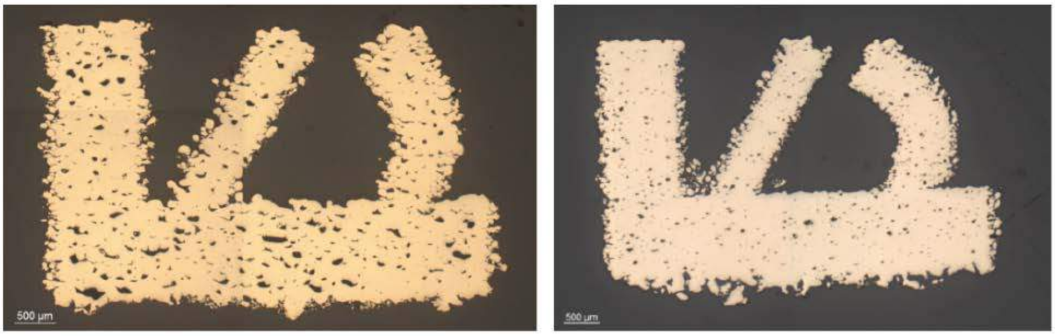


Figure 16 18k yellow gold samples with two sets of parameters. Left: v = 50mm/s, hatch distance 27µm, resulting porosity 7%. Right: v = 250mm/s, hatch distance 36µm, resulting porosity 3.5% [34].

The main process to treat the powder and reduce the reflectivity is sulfidation. As shown in [34] we pass from 3.5 % (look at Figure 16 in the right imagine) to below than 1.5 %, that is really interesting result in terms of quality of our piece. We also had an increase of the flowability of the powder.

Alloy modification

An important aspect that we must take in account when we add alloyed elements is that the content of the gold must to be 75 % in order to guarantee 18-karat. In the below table we are indicating various type of composition and then the results that were achieved in [33] and [34].

Table 6 Composition of the investigated alloys in mass %[33]

Alloy	Au	Ag	Cu	Ti	V	Fe	Co	Ge
3N	75.1	12.4	12.5					
Ti001	75.2	11.7	12.8	0.3				
V001	76.9	10.5	12.3		0.3			
Fe001	75.3	12.1	12.5			0.1		
Co001	75.2	11.7	12.7				0.4	
Ge001	75.1	11.8	12.8					0.4

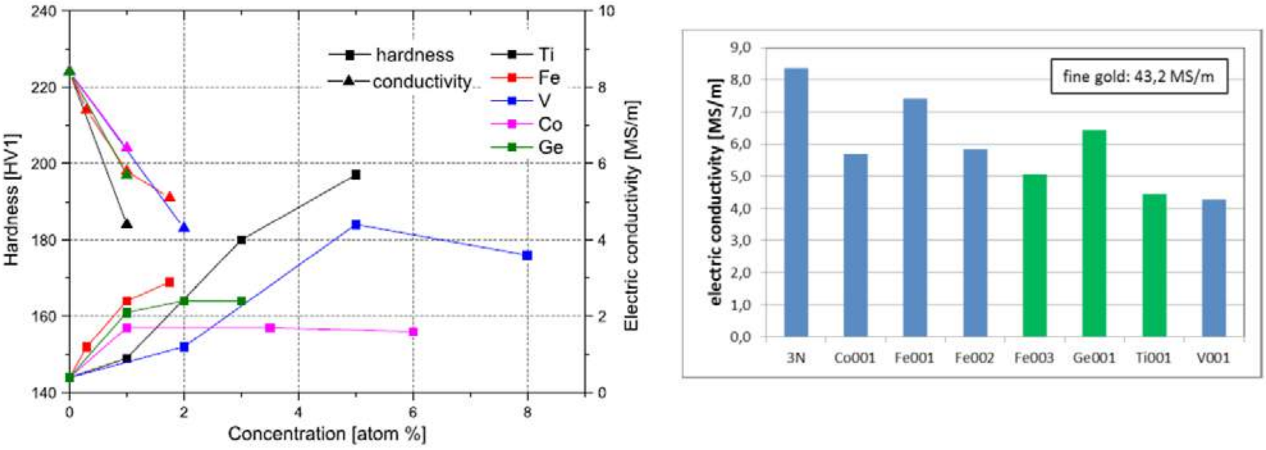


Figure 17 Left: Vickers hardness and electric conductivity of selected alloys in the annealed condition as function of the concentration of the fourth element [33]. Right: Electric conductivity in Mega Siemens per meter (MS/m) of a standard yellow gold alloy (3N) and of alloys with additions of Co, Fe, Ge, Ti and V. For comparison: the electric conductivity of titanium is ca. 1MS/m. [34]

In Figure 17 we are talking about electric conductivity but by the means of Lorenz number L in the Wiedemann-Franz law we can coupled it with thermal conductivity (it is valid for metal) [40]. As shown in previous graph we can easily understand that Ti and V has the most beneficial effect on the reduce of electric conductivity (and so the thermal conductivity). With them we have also an increase of hardness that is one characteristic that is necessary in an external component of a watch (like watch case, bezel and strap); this means that we can avoid scratches that are detrimental for the aesthetics of the final product.

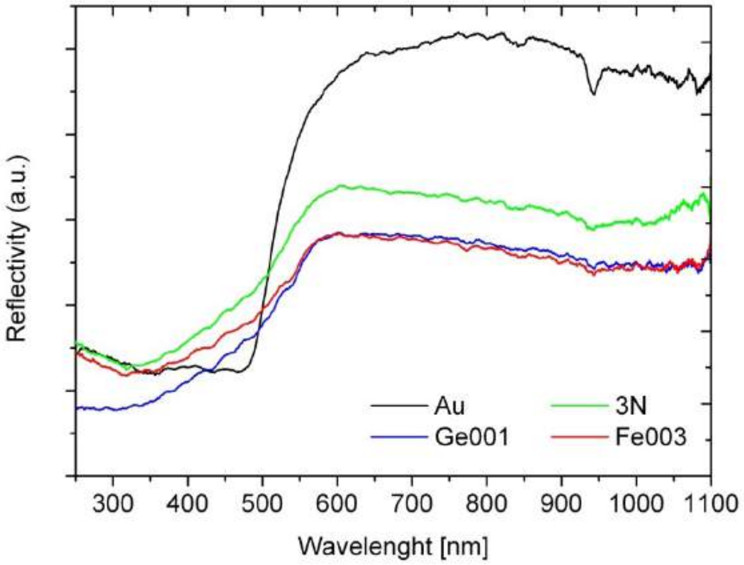


Figure 18 Spectral reflectance of gold compared to standard yellow gold (3N) and the modified alloys.[34]

By the Figure 18 we clearly understand that the addition of alloying elements reduces a lot the reflectivity of the gold.

One last improvement that is achievable by alloying elements is the reduce of porosity, this is due to the two previous benefits effect (reduce of reflectivity permit a major absorption of energy and reduce of thermal conductivity, hence decrease of heat dissipation).

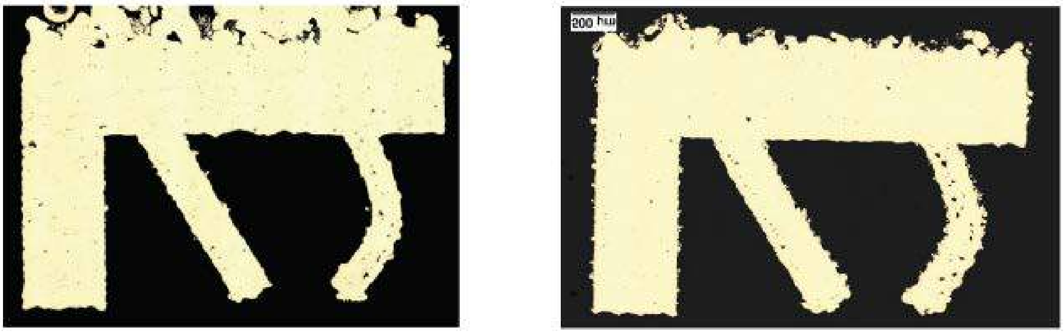


Figure 19 Porosity of modified gold alloys for the same laser parameters. Left: Fe containing alloy; 0.3% porosity. Right: Ge containing alloy; 0.1% porosity.[34]

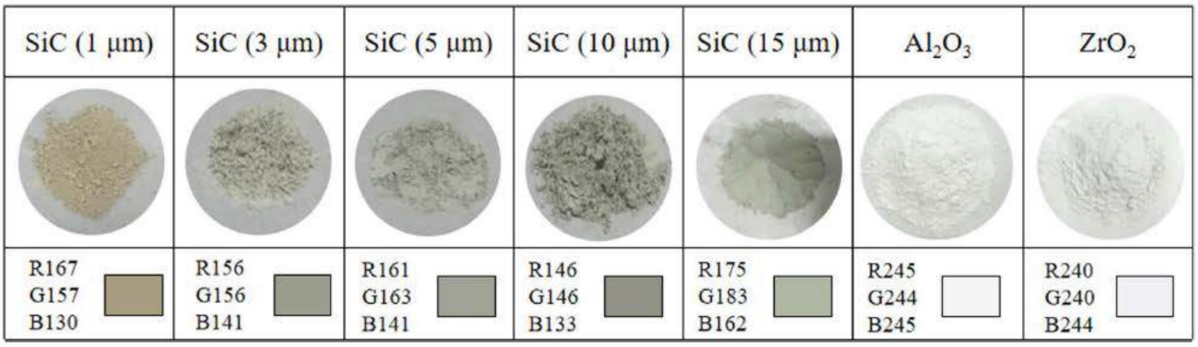
2.4. Ceramic

Introduction

Ceramic is one of the hardest class of materials, so they are resistant to scratches. About this we want to underline that gold it is not much resistant to the scratches, so if we want to maintain the structure of our watch constant for long time, we need to buy a ceramic’s one. They also will not corrode or cause allergenic reaction, because they are inert materials. They have less weight than metals. On the other hand, due to high hardness we must consider that they are fragile material, so we need some improvement to avoid fragile. They have low toughness, high hardness, and high fragility so we have many problems to machine them.
As for gold, ceramic is used to produce watch case, bezel and bracelet and can be produced in different kind of colours, that is an interesting feature for the customers tastes.

Problems

As we have underlined in the introduction, we have the main problem of the fragility. Another problem correlated to ceramic is their high tendency to form cracks due to very high cooling rates during the process. This induce internal stresses, and if the stresses are sufficiently high, crack initiation and propagation may occur [35]. After this we see that during stereolithography as shown in [43] we have different behaviour of the powder subjected to the UV violet by the machine. The larger the absorbance value of an object, the deeper colour the object exhibits. We are interested in it because the higher the absorbance value, the less light acted on the polymer networks, and the bad curing ability exhibited [43]. Typical materials that are used in watches such as Al_2O_3 (alumina) and ZrO_2 (zirconia), are in white colour. However, SiC (also use in watch industry) ceramic is usually in grey or dark colour. By this we can easily understand that for Al_2O_3 and ZrO_2, have low absorptivity and high curing; SiC has the opposite behaviour (this is shown in Figure 21).



SiC (1 μm)	SiC (3 μm)	SiC (5 μm)	SiC (10 μm)	SiC (15 μm)	Al_2O_3	ZrO_2
R167 G157 B130	R156 G156 B141	R161 G163 B141	R146 G146 B133	R175 G183 B162	R245 G244 B245	R240 G240 B244

Figure 20 Colours of the raw materials [43]

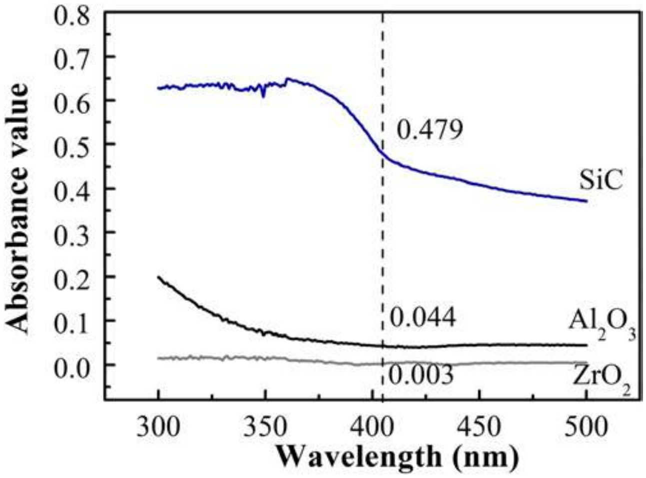


Figure 21 Absorbance values of Al2O3, ZrO2, and SiC particles (particle size: 10 µm) [43]

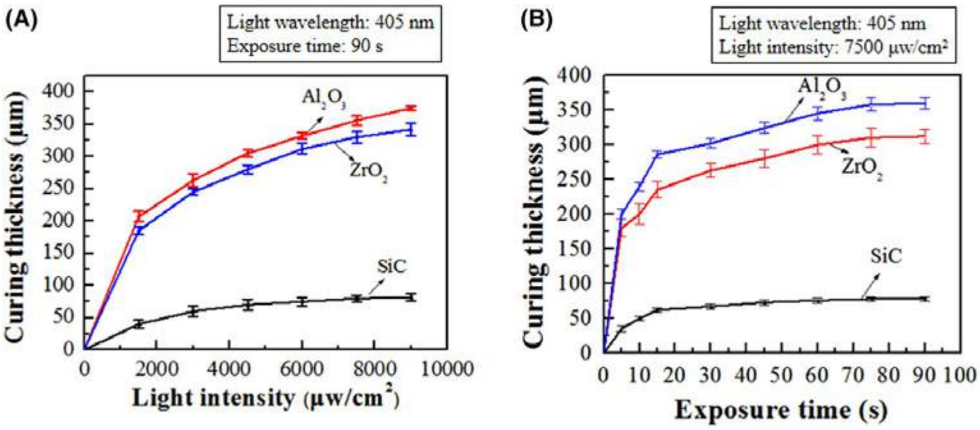
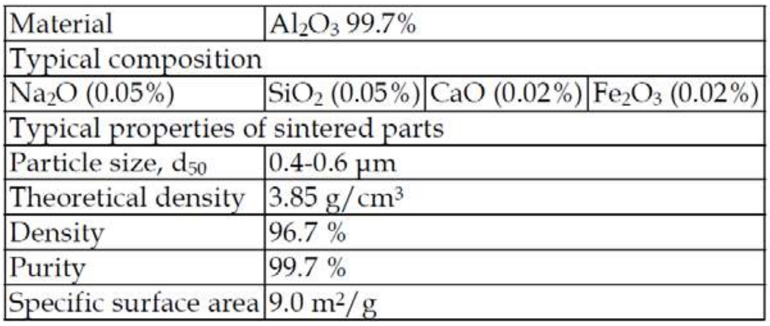


Figure 22 Curing ability of Al2O3, ZrO2, and SiC slurries (particle size:10 µm; solid loading: 30 vol.%; lightweight wavelength: 405 nm): (A) curing thickness vs. light intensity; (B) curing thickness vs. exposure time [43]

Solutions

In this chapter we want to explain some interesting results reached by zirconia doping on alumina.

Table 7 Properties of Al2O3 powder [36]



Material	Al_2O_3 99.7%		
Typical composition			
Na_2O (0.05%)	SiO_2 (0.05%)	CaO (0.02%)	Fe_2O_3 (0.02%)
Typical properties of sintered parts			
Particle size, d_{50}	0.4-0.6 µm		
Theoretical density	3.85 g/cm^3		
Density	96.7 %		
Purity	99.7 %		
Specific surface area	9.0 m^2/g		

As we mentioned before, we need to avoid that our watch breaks easily, because its high fragility. A reduction of crack formation due to the high cooling rate was reduce by the adding of zirconia [35]. This is due two facts:

- Zirconia doping refined the microstructure (it strengthen the ceramics)
- The accumulation of the dopants at grain boundaries toughen the alumina

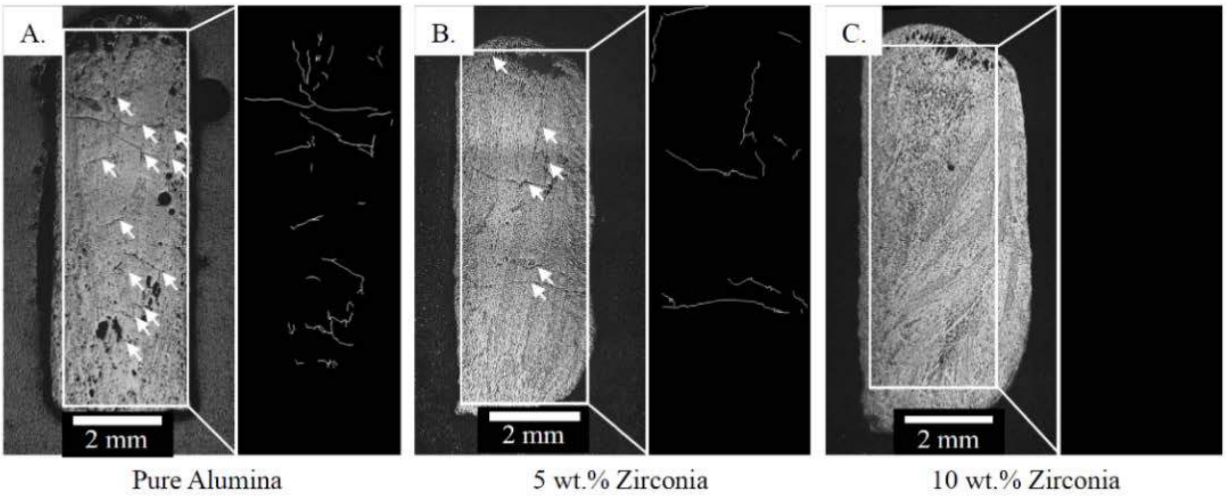


Figure 23 Cross-sectional cracks (left) as highlighted for crack length analysis (right) within typical samples printed at a laser power of 275 W and a scan speed of 1000 mm/min: A.pure alumina, B.5 wt.% zirconia and C. 10 wt.% zirconia [4]

The hardness of zirconia is less than alumina, this help to decrease that property (pure alumina showed an average value of 1880 Hv, instead by 10 wt.% zirconia they reach 1680 Hv [35]). Unfortunately, we have an increase of the porosity and an altered pore size distribution, so we need to keep in mind this and perform a trade-off, in order to achieve what we want from our ceramics.

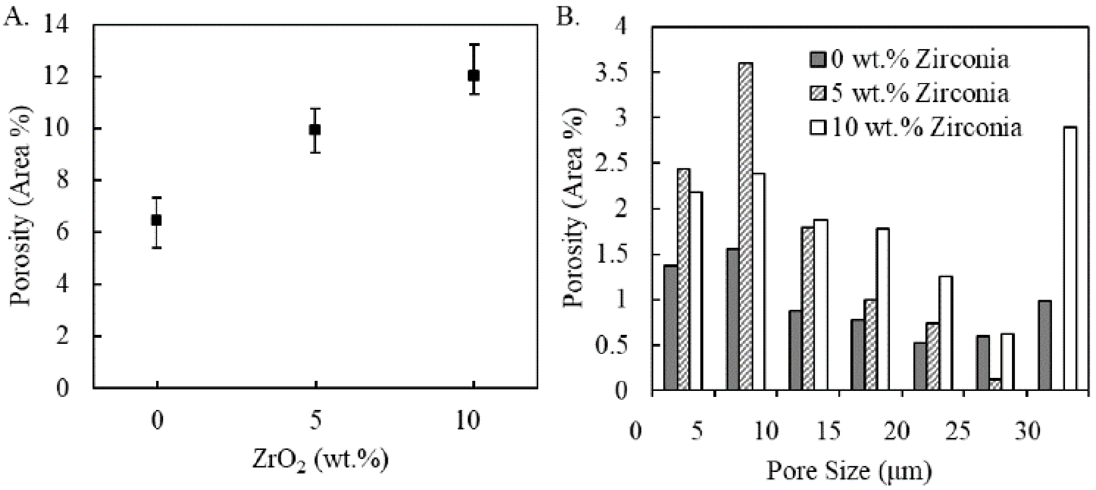


Figure 24 Porosity analysis of samples printed at a laser power of 275 W and a scan speed of 1000 mm/min, where A. shows porosity area percentage measured at the middle region of the samples, and B. is a weighted histogram showing pore size distribution [35]

Colourful Zirconia

Zirconia is typically white in colour [46]; here we want to explain how the stereolithography process change by changing the colour of zirconia. Colourful zirconia contains inorganic colorants, that are used as ceramic colorants for their excellent thermal and chemical stability at high temperatures [44]. In [44] were analysed three types:

- ZrO2-CoAl2O4 (blue)
- ZrO2-ZrSiO4(Fe2O3) (red)
- ZrSiO4(Pr2O3) (yellow)

As shown below we have the variation of the absorptivity, in particular an increase, with the arise of the colorant content. This mean that we have decreased the cure depth with the increase of colorant content.

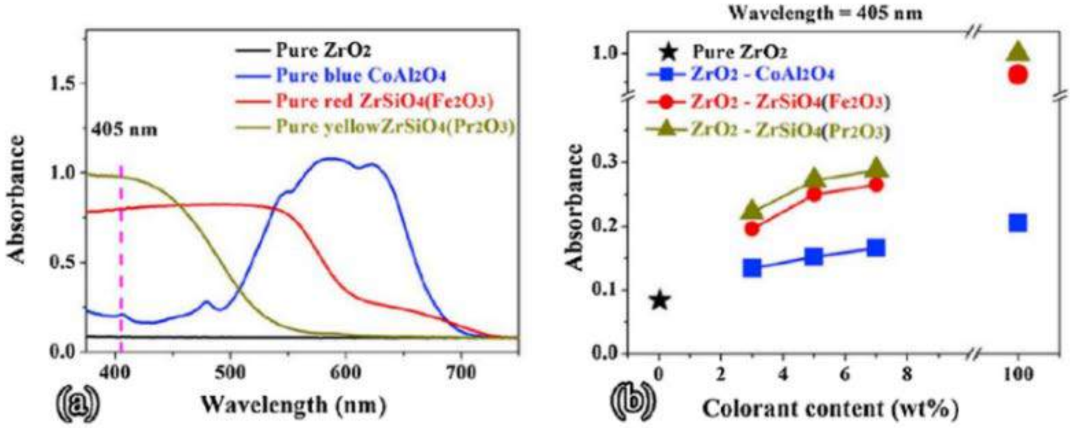


Figure 25 The light absorbance of ceramic powders under a wavelength from 350 nm to 800 nm (a), and absorbance of ceramic powders with different colorant contents under violet wavelength of 405 nm (b) [44]

In order to investigate the effects of ceramic absorbance on cure behaviours, the cure excess width of suspensions is also evaluated, as shown in Figure 26

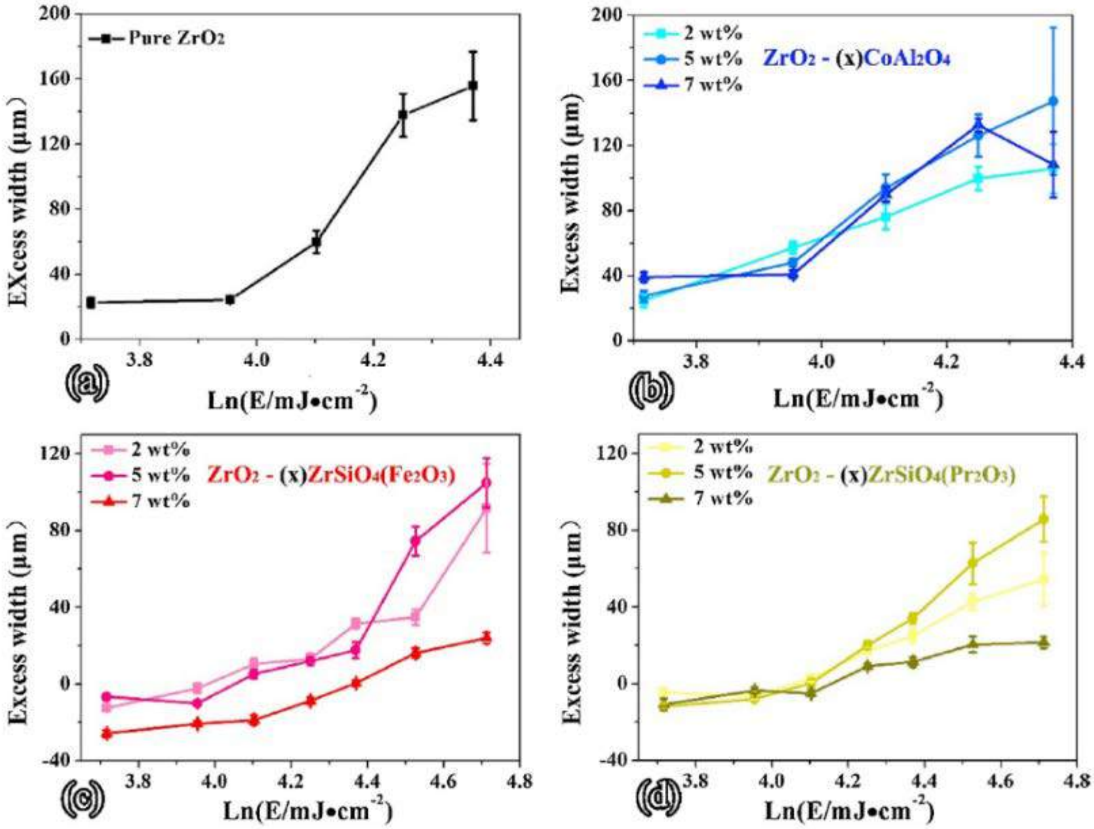


Figure 26 The excess width of colorful suspensions vs. logarithm of incident energy, (a) pure ZrO2 (3Y-TZP) suspension, (b) blue suspension (ZrO2 + CoAl2O4), (c) red suspension (ZrO2 + ZrSiO4(Fe2O3)) and (d) yellow suspension (ZrO2 + ZrSiO4(Pr2O3)) [44]

By this graph we can clearly see that the colorant has a positive effect on the excess cure width.

2.5.Nylon

The main component of the watch that we can produce with polymer material is the strap. We develop our research on one of the main polymer materials that are used in the straps of the watches: nylon. Nylon, also called Polyamide (PA) is a widely used polymer in the additive manufacturing sector. This thermoplastic is available in powder or filament form [38]. The main problem that we have in 3D printing of this material is its hygroscopic (it easily absorbs the moisture). The moisture absorbed, cause creation of bubbles during the heating up of the material; this creates a poor output. This property is helpful in the post-processing by absorbing fabric dyes and spray paints [39].

Nylon Pros:

- Well fitting
- Durable and lightweight
- Affordable
- Variety or colours and styles
- Ideal for metal allergic people

Nylon Cons:

- Becomes hot and can cause wrist to sweat
- Easy to discolour

There are different types of Nylon, but the main are: Nylon 6, Nylon 6-6, and Nylon 12. An interesting development on the regeneration and recycling process of Nylon-6 waste, have been reached by Aquafil group through the ENCONYL PROJECT; they have studied a three-step system to produce Nylon-6 from 100% regenerated waste materials (fishing nets abandoned in the oceans and aquaculture, scraps from carpets and various industrial nylon products)[48][47].

Figure 27 3D printed Apple Watch bands (The Pulse, Obsidian and Aurora Apple Watch bands)

3. Applications of AM in the watch industry

Introduction

This chapter shows the applications to the watches that we have been found: these applications are grouped in subchapters depending on the AM technology that is used for its fabrication. In some cases, it will be shown the post-processes and the treatments that are applied on the worked part to achieve a certain surface quality or a certain level of resistance to scratches. Every company uses its specific technology and, in some cases, its specific material, for this reason it has not been possible to go too much in details. However, some interesting applications are described in the following paragraphs. In the first paragraph we are not describing applications about additive manufacturing in the watch industry for the only reason that we want to give the possibility to understand what the state of the art on the production of ceramic part by watch companies is. We are talking about Ceramic Injection Moulding that we decide to describe it in the Appendix. As we can see in this chapter, there are a lot of applications about it compared to additive manufacturing ones.

3.1. Applications of the CIM

Rado's models

Rado of Lengnau, Switzerland, part of the Swatch Group, was one of the first of the luxury watch makers to turn to Ceramic Injection Moulding for its watch pieces in the 1990s and stated at the relaunch of its Ceramica brand in 2016 that high-tech ceramics offer an attractive combination of lightness and scratch resistance. Seven ceramic colours: black, white, plasma, grey, brown, green and blue – are now featured in Rado's collections [1].
Grey ceramic (Figure 28) debuted in the Ceramica collection with two finishes: a subtle, earthy sandblasted matt and a perfect high-gloss polish, a testament to the versatility of this remarkable material [1].

Figure 28: Rado's model in grey ceramic [1]

The 43 mm case in the watch in Figure 29 left is manufactured using one of Rado's signature materials, plasma high-tech ceramic. To create this material, finished white ceramic components are fired in a plasma furnace, where gases activated at 20,000°C give rise to a metallic shine on the surface [1].

Rado’s thinnest-ever Ceramica timepieces (Figure 29 right) come in four colourful new ceramic variations: inky blue, forest green, lunar grey, or chocolate brown. This new collection is characterised by an extremely thin 4.9 mm profile [1].

Figure 29 Left: Rado’s model with grey/brown high tech polished plasma ceramic case. Right: Rado’s model with features polished plasma CIM cases available in grey, blue, green or brown [1]

Omega SA

Omega SA, based in Biel/Bienne, Switzerland, is also part of the Swatch Group and the luxury watchmaker unveiled some noteworthy new ceramic models. These included the new Seamaster Planet Ocean Big Blue (Figure 30 left) which has a case made entirely from blue zirconia ceramic [1]. As well as the solid blue case, the watch features a blue ceramic dial with an orange GMT track. Adding sparkle to the blue dial are hands and indexes in 18-carat white gold with a white coating. A blend of orange rubber and ceramic covers the first fifteen minutes. The colouring begins with pigmentation at the early stage of preparing the ceramic powder [1].

For a ceramic Speedmaster (Figure 30 right) today, the shape of the case body is first injection moulded from a special zirconia-based powder. The case bodies are then debound followed by a sintering process at temperatures reaching in excess of 1400°C, making the zirconia ceramic hard and scratch-resistant. For such a tough material, it then takes machining with diamond tools to add any defining edges and grooves. A three-hour plasma treatment in a 20,000°C furnace then paves the way for precision laser engraving[1].

Figure 30 Left: Omega’s Seamaster Planet Ocean Big Blue[1]. Right: Omega’s Speedmaster Racing model [1]

TAG Heuer SA

TAG Heuer SA, based in La Chaux-de-Fonds, Switzerland, first presented its Carrera Heuer 01 where the 45 mm case, bezel, lugs, and case middle are produced using matt black ceramic (Figure 31). The ceramic parts are micro-blasted to achieve the matt black finish [1].

Figure 31: TAG Heuer's Carrera Heuer 01 [1]

Hublot SA

Hublot SA, Switzerland, first introduced zirconium oxide ceramic materials for watches in its Big Bang series, launched in 2005, featuring satin black and white as well as bright red and yellow. In 2012, Hublot introduced a new material for its watches, where 24 carat gold is fused with boron carbide to create a "Magic Gold" alloy (Figure 32 left). To produce watch parts from this new alloy, the boron carbide powder is first injection moulded to produce the required shaped part and, after debinding and sintering, a 24 carat gold alloyed with 3% molten liquid gold is injected at high pressure and high temperature into the porous ceramic. The gold fills the pores in the ceramic creating the Magic Gold effect (Figure 32 left) [1].

In 2017, Hublot introduced ceramic designs for the "Click Italia Independent" women's luxury range, developed in partnership with the Italian design company Italia Independent (Figure 32 right). The 39 mm diameter timepiece comes in three different combinations using scratch resistant polished black ceramic cases and black plated steel deploying clasps on velvet straps. The black ceramic case features ten diamond indices on the dial and a diamond studded dial [1].

Figure 32 Left: Hublot's Magic Gold. Right: Hublot's new ceramic 'Click Italia Independent' women's luxury watch [1]

Seiko watch

In 2016, Seiko Watches Corp. of Japan expanded its Grand Seiko in the sport field by presenting the Black Ceramic Limited Edition for Spring Drive watches using a combination of a zirconia ceramic outer case and a titanium inner case. The zirconia ceramic is stronger and tougher than any other fine ceramic and seven times harder on the Vickers scale than stainless steel. The new Grand Seiko (Figure 33) has the flat case which has the ceramic edges on the polyhedral shape that are polished to a mirror finish and produce the intricate overlapping reflections [1].

Ceramic does not typically have reflective properties, but multiple polished surfaces on the case reflect light even in dim conditions, creating a sharp, crisp visual impression. The watch is comfortable to wear, primarily because of the lightweight hybrid titanium-ceramic case and bracelet. As the zirconia ceramic parts are raised slightly above the level of the titanium, the bracelet is virtually impervious to scratches and will retain its as-new appearance just as long as the watch case itself. Given the technical difficulty of polishing ceramics, the ceramic parts in the centre of the bracelet are polished to a mirror finish [1].

Figure 33: The limited edition Grand Seiko Spring Drive Chronograph GMT [1]

Rolex

Rolex, of Plan-les-Ouates near Geneva, Switzerland, adopted black ceramic bezels in 2005 using its Cerachrom process, developed and patented by the company, which allows this watch component to be produced as a single piece in two distinct colours. The Rolex Yachtmaster II's Cerachrom bezel features (Figure 34) well defined minute markers and polished, raised graduations on the ceramic inlay, which stand in relief against a sandblasted, matt black background [1].

Figure 34: Rolex's Yacht-Master [1]

Lehmann watch

Uhrenmanufaktur Lehmann has been producing watches in Schramberg, a centre for watchmaking in the Black Forest area of Southern Germany, since October 2011. The watches are characterised by their round cases and slim bezels which culminate in closed horns that form a distinctive frame to the wristband (Figure 35). The dark ceramic surface of the watch case has a striking matt shimmer that changes from black to grey, depending on the lighting conditions [1].

Figure 35: Lehmann Schramberg's Intemporal Keramik [1]

3.2. Applications of the Material Extrusion

Tourbillon watches

3D printed Tourbillon watch, shows in Figure 36, was built by Christoph Laimer, a Swiss engineer. This is an actual watch, with a whirlwind, that is almost entirely 3D printed. It is a pocket watch, not a wristwatch, not very accurate and only runs for about 30 minutes. It was manufactured using an affordable consumer level 3D printer, an Ultimaker 2, shows in Figure 37 [8].

Figure 36: The 3D Printed Tourbillon Watch [8]

Figure 37: Ultimaker 2 printer [21]

The whole thing is 98mm in diameter and 93mm tall. The entire watch is 3D printed: every gear, escapement component, the case, even the balance spring and mainspring. The only non-printed parts are the metal pins used as the axes for the gears, and some screws and washers. This watch was built by arranging his gears in a vertical stack rather than the usual horizontal arrangement (Figure 38) [6].

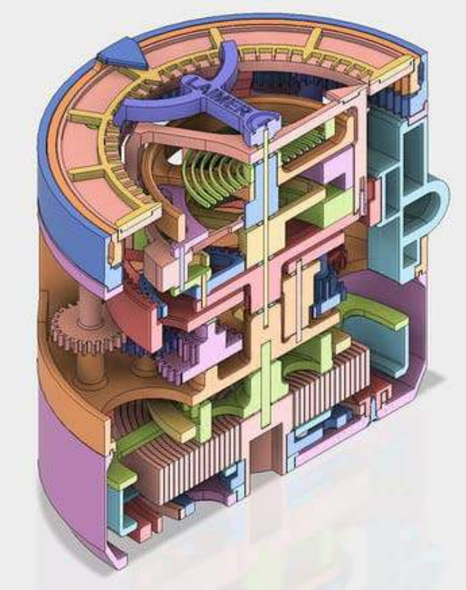


Figure 38: CAD Cutaway of the 3D Printed Tourbillon Watch [6]

A major consideration in any 3D printing project is the relation between the nozzle diameter (X/Y resolution) and bed size (how big a printed part can be, in X/Y/Z). These two variables determine the overall scale at which the project can be printed, they determine how small you can make your watch. Usually, traditional watch movement architecture is not compatible with ratio between nozzle diameter and bed size found in most 3D printers. So, instead of using traditional horizontal movement architecture, Laimer instead built upwards, layering parts vertically. It is used gears with steel pins running all the way through them, on which the gear rotates; this allows for higher strength and low weight in the movement construction, and for the ability to mount gears co-axially. Figure 39 shows that the escape wheel and balance share the same axis [6].

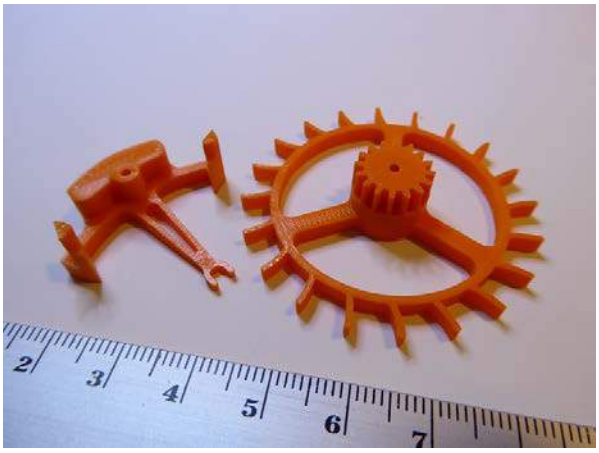


Figure 39: Escape wheel and pallet fork [6]

The mechanical clock, shown in Figure 40, demonstrates that 3d-printing is not just for decoration. It is possible to create intelligent, living things. The clock has an anchor escapement, and a balance-wheel with a spiral spring. The clock shows seconds, minutes, and hours. The winding has a nested planetary gear, which allows that the clock continues to run, while winding up. It is made by PLA and printed with Rapman 3.2, shown in Figure 41 [8].

Figure 40: 3D printed mechanical Clock with Anchor Escapement [8]

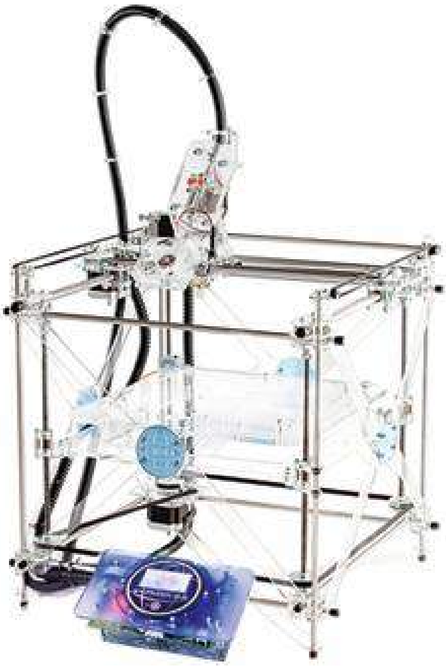


Figure 41: Rapman 3.2 3D printer [22]

3.3. Applications of SLM and SLA

Venus Concept Watch 1.0

This application is an interesting work developed by the Innovation Design Engineering Program of the Royal College of Art which has as a principal scope to produce a watch that can be survive to difficult environmental situation. In particular we are talking about equipment that need to support the environment conditions of Venus and Jupiter. Specifically, at the surface of Venus we reach 460 °C and 92 bar, and also the high amount of CO_2 in the atmosphere means that the ambient is very corrosive. This project is a first step, in fact they need more study to develop a functional watch that effectively can work on that environment, but good achieved were reached by this work that is described in [71]. The second phase will be tests that need to be done at NASA’s Venus environment Test Chamber, in order to see the effective behaviour of their watch at that critical conditions.

So as a first version of this watch they developed a waterproof watch that resist up to 100 bar, using 3D printed titanium body, sapphire crystal for the glass, nylon parachute ribbon for the watchband, and a laser cut 2D woven carbon finer sheet for the face. Thanks to the use of additive manufacturing, they were able to reach thin and complex internal and external structures and also they achieve a light, but strong metal part [71].

Focusing on the part that were created by 3D printed, as shown in the [71], the best technology to print titanium and stainless-steel, which are used for the housing of the watch, is SLM. Other attempt were done by SLA (only for the production of plastic parts) and EBM (Electron Beam Melting, which is a solid freeform fabrication method), but in the first case the material was too much soft and in the second the accuracy was lacking (as we can see in the Figure 42, Figure 43, Figure 44 and Figure 45). It was also discovered that the printing of stainless-steel does not require a surface finishing, so not necessarily we have post-processing, that is very good to reduce the time and the costs of the process.

Figure 42 Plastic Parts of Watch 1.0 made by using SLA[71]

Figure 43 this EBM printing method does not produce the desired parts with the right accuracy [71]

Figure 44 SLM printed part made by using titanium[71]

Figure 45 SLM printed part using stainless steel as powder[71]

Figure 46 Final fabricated Watch 1.0[71]

Hoptroff Watch

They developed a 18k watch case that is shown in Figure 47 with SLM process. The surface finish and the luxury are up to the mark in it. Beginning with producing a prototype from plastic, Hoptroff went on to figure out how to 3D print with gold. They first tested casting a 3D-printed wax model in metal with a lost-wax process. With a printer such as the $49,650 Solidscapes 3Z Max wax printer, it's possible to create a 3D object out of wax and cast it in metal. Because there were limitations posed by the strength of their wax moulds, however, Hoptroff, instead, pursued the other method of printing in metal, direct metal laser sintering. By fusing bits of gold powder together, DMLS (Direct Metal Laser Sintering) gives Hoptroff the ability to produce more intricate shapes in 18 karat gold. And, after fine-tuning their design process, they were able to move from ruttier gold watch casings to something a little more refined [89].

Here we put some information about that watch [87]:

- Additively manufactured, 18k 3N Yellow gold
- Height 11.6mm
- Weight as built 40.8g, weight as finished milled and polished 34.1g
- Time from design finalisation to finished part - 1 week

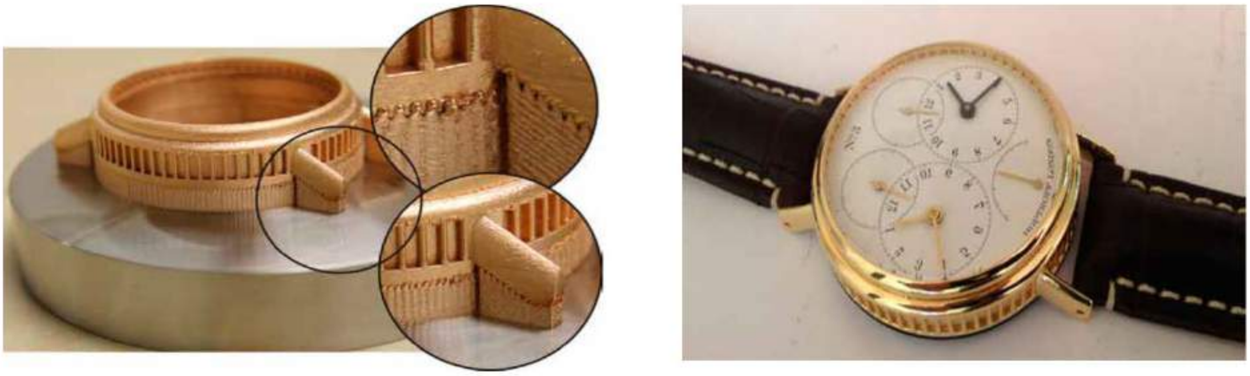


Figure 47: SLM printed watch case using 18K gold[62]

Figure 48: Left: part made with SLM without post processing. Right: same part made with SLM with post processing [89]

The watchmakers show a side-by-side comparison between a watch that has been SLM printed and a watch that has been cast using traditional subtractive manufacturing, with the details printed into the sides of the watch face attesting to the possibilities of refinement that can be achieved with SLM printing [89].

Figure 49: Left: Part Made by SLM. Right: Same Part Made by Traditional [89]

Watch Clasp

Here we are putting an example of an element that is used in wristwatch for closing them. It has been made by SLM, using silver powder. In the next table we show some parameters that have been used during the processing of this piece.

Table 8 Parameters for silver powder [61]

Power P [W]	20
Speed v [mm/s]	10
Pulse frequency f [kHz]	5
Hatching hd [µm]	50
Layer height e [µm]	40

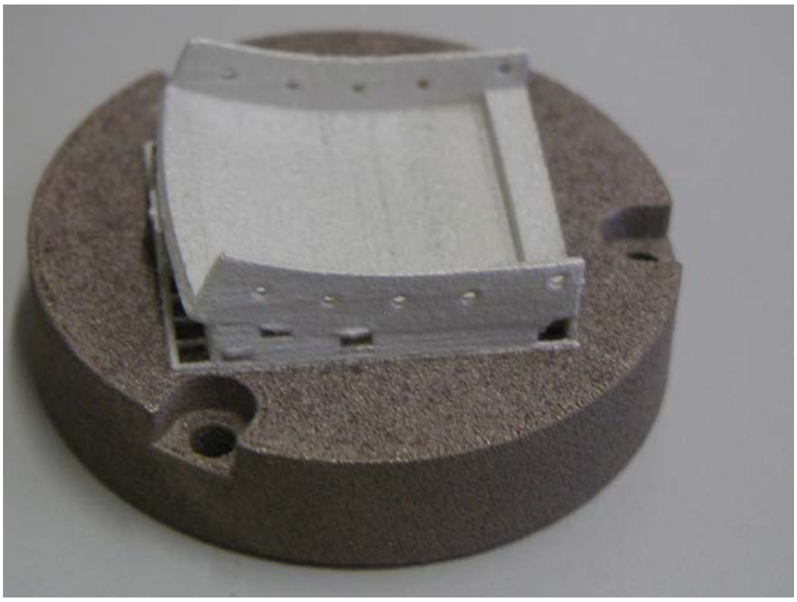


Figure 50 Watch Clasp made by SLM printing[61]

3.4. Applications of SLS

ALB watches

ALB, “Atelier le Brézéguet” is a french brand from Toulouse, founded by Vincent Candellé Tuheille and Simon-Pierre Delord. This company is specialized in watches, and more precisely, in wearable 3D printed watches. These parts are a mix of craftsmanship and modern technologies. Selective Laser Sintering is the perfect method to 3D print the plastic of the ALB watches and give them this artistic look. The black rings, on the top and the bottom of the watch, are printed with polyamide (Figure 51) [23].

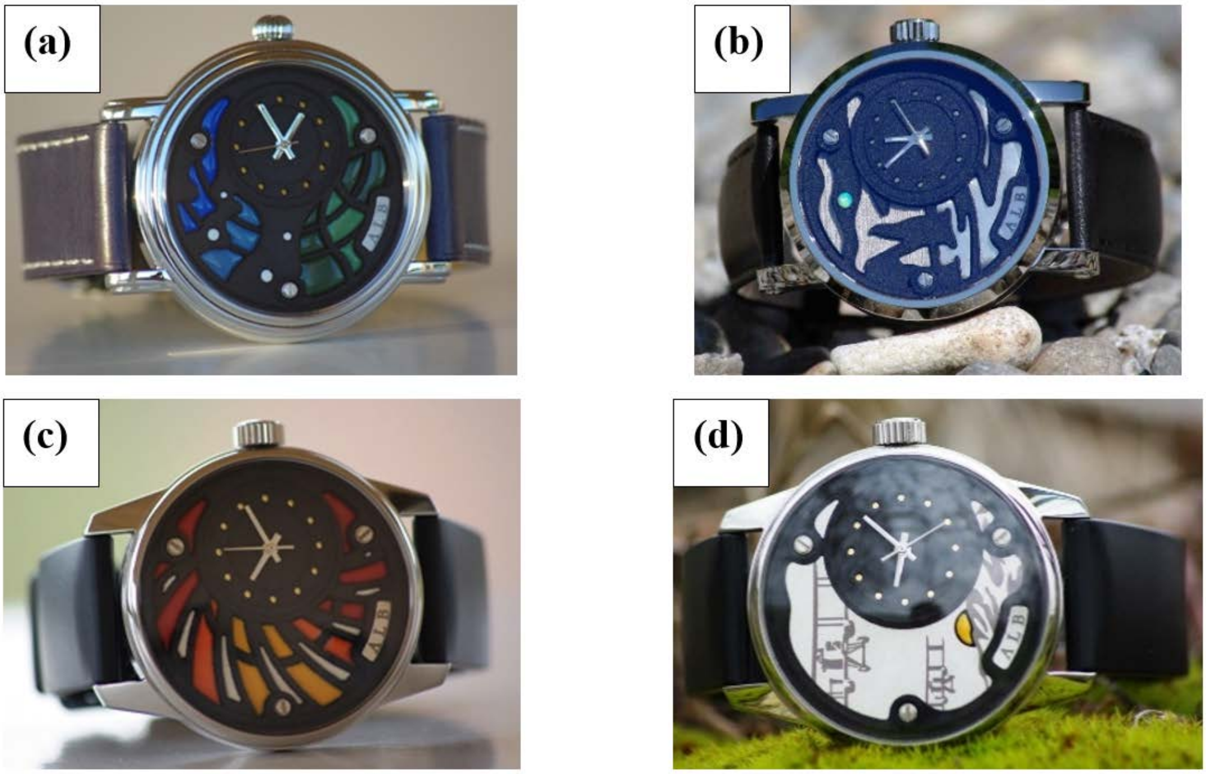


Figure 51 (a) Model ALB 000 «Balade au Brézéguet». (b) Model ALB 200 «Promenade à Etretat». (c) Model ALB 100 «Secondes d’Eclipse». (d) Model ALB 110 «Vers le bout du monde»

3.5. Applications of the BJ

Uniform Wares

Uniform Wares, a luxury watchmaker estabilished in 2009, partnered with Betatype to explore the advantages of additive manufacturing (AM) technology, pushing the boundaries of design in an industry traditionally centred around heritage. They produced a superior quality, mesh 3D printed titanium watch strap which is featured in Uniform Wares' 2019 collection. Uniform Wares teamed up with Betatype specialists in advanced design and additive manufacturing, to design and develop a unique woven AM watch strap for their new PreciDrive M-Line collection. The watch strap is manufactured by combining Betatype's unique scanning technologies with Renishaw's AM250 additive manufacturing technology. Using a titanium T5 alloy material made it possible to create a strong, yet lightweight 'metal fabric' strap which has already gained popularity and prestigious reviews from clients. Previous Uniform Wares watches had featured a mesh-like bracelet manufactured using more traditional methods. They used a huge, cumbersome machine to weave steel cable into the mesh pattern, which they then had to cut to size and weld working parts onto it. When Betatype presented an idea that could simplify the process by allowing the woven strap to be printed in any texture or grain, incorporate new materials and produce less waste, Uniform Wares was keen to get involved. Every element of the watch bracelet has been engineered exactly as it needs to work. The radius at which it curves, the flexibility and stiffness at each point, every link incorporates fine adjustments. It represents bespoke engineering at every point (Figure 52) [12].

Figure 52: Metal mesh NATO strap prototypes [12]

Betatype applied its unique multi-scale approach to exert greater geometric control over the watchstrap designs and used Renishaw's AM technology to bring the Uniform Wares watchstrap to life. Taking full advantage of working together to create a design specifically for Additive Manufacturing, Uniform Wares and Betatype were able to take the most of additive technology to create a strap that was more accurate and intricate than any previous design. The bracelet is made up of over 4,000 interlocking links and weighs just 10.5 g (Figure 53) [12].

Figure 53: Uniform Wares M40 PreciDrive calendar watch in brushed steel with natural titanium bracelet [12]

The asymmetric design of these links allows each side of the strap to have a different bend radius, meaning it can easily fit over the hand, allowing flexibility, whilst remaining secure on the wrist. The strap uses microscopic ‘teeth’ and a new type of directional clasp interlocking with the mesh itself, which can only be achieved using additive manufacturing, to hold the watch in place. The product is superior in terms of quality and level of detail and has demonstrated the power of AM and the freedom it can bring to design for manufacture [12].

Holthinrichs watches

Michiel Holthinrichs, the founder of Holthinrichs Watches, is working with a Renishaw Additive Manufacturing Solutions Centre to build up his knowledge about the potential of metal additive manufacturing and to speed up the overall manufacturing process for his high-end, limited-edition watches. His first design Ornament 1 combines traditional watchmaking elements, including a Swiss movement with manual winding and a design inspired by classic watches of the 1950s, with the new technology of metal 3Dprinting, which was used to produce the case, crown and buckle. Michiel worked with the bureau to 3D print prototypes and the first Ornament 1 watch on its Renishaw AM250 (Figure 54) [13].

Figure 54: Renishaw AM250 [25].

The case, crown, and buckle of the Ornament 1 (Figure 55) were metal 3D printed in stainless steel 316L. The watch case has a diameter of 38 mm and is only 10 mm thick; it has a raised inscription of the Holthinrichs brand on its edge with the words “stainless steel”, “3D printed case” and “Swiss movement”, in capitals on its reverse. These details were achievable only by using metal AM [13].

Figure 55: Holthinrichs Ornament 1 watch [13]

The batch of watches took approximately thirty hours to print on the Renishaw AM250 system. Post-processing, including machining of the parts, was outsourced and they were returned to Michiel, who finished them with hand filing and polishing. The post-processing, assembly and adjustment by hand took a further thirty hours per watch. Michiel noted, however, that customers seemed to be less concerned by the method of manufacture, but rather more by the details in the design which are not offered by other watches. The Holthinrich’s signature which appears as raised fine script on the edge of the case could not be achieved by traditional manufacturing and highlights the capability of Renishaw’s high-performance AM systems to produce highly precise and fine detail features. Based on the success of the Ornament 1 in stainless steel, Michiel wished to offer the watch design in an alternative material. Renishaw recommended titanium because it is possible to achieve a highly polished finish hand it is suitable for investigating chemical post processing which could help reduce finishing time. Also, titanium is lighter than stainless steel and this would provide Michiel with an additional point of differentiation in his Ornament 1 design range [13].

Barrelhand

Barrelhand, an upstart indie watchmaking brand based in San Francisco, create a new watch called Project 1 (Figure 56), in which its components are produced through various types of 3D printing methods. The use of 3D printing reduces costs dramatically and allows them to manufacture parts that would not have been possible otherwise [14].

Figure 56: Barrelhand Project 1 [14][86]

Figure 57 How we read the minutes in this watch [86]

The case is made in titanium. The Metal Binder Jetting is capable of a level of precision that is four times thinner than a human hair, which allows the brand’s design team a level of flexibility that is simply impossible with traditional methods. The Project 1 has an avant-garde look that nicely complements the advanced tech behind its production. From looking at the dial, we note that the current hour is read with a jumping mechanism at the top of the dial, and the minutes display is located at what would normally be 6:00. While the jumping hour is a traditional complication in classical watchmaking, the linear minutes display used in the Project 1 is more novel. The design is inspired by the rotation of a vinyl record, with the base dial making a full rotation once every hour. There is a cam path cut into the dial, which is traced by a needle as it rotates. This rotation guides an indicator up and down, which allows for the reading of the minutes. A circular indicator at the bottom of this minute's column tells the user which side to read (the downward trajectory displays minutes 0-30, up is 31-60). Because of the wide diameter of the rotating dial, a leveling system was designed to protect it against impacts. Ruby bearings have been utilized around the perimeter of the dial, allowing it to spinun obstructed while providing a level of resistance to shock. Even the jump hour, perhaps the most traditional single element of the watch's design, has been tweaked by Barrelhand to offer greater functionality and reliability. The Project 1features a "Geneva Jump Hour," which can be set forwards and backwards while using fewer total components. Like the leveling system, the Geneva Jump Hour makes the Project 1 more robust overall, ensuring that it is actually wearable in the real world, and not simply a display piece, or a curiosity. Everything from the straps and cases down to the crystals and gaskets are made in Barrelhand, with exception to the 11 3D printed steel parts made in Germany, and a precision Swiss engine to power the in-house time displays. The hour wheel is held in place by a top plate made with metal binder jetting, making it the world's first 3D printed steel movement bridge in a production watch [14][86]. They use stereolithography and multijet printing for the plastic prototypes. For production they use a mixture of DMLS (Direct metal laser sintering, which use a high-powered ytterbium fiber laser), that produce for instance the strap inserts, and MBJ (Metal Binder Jetting). Actually, their current capabilities allow them to 3d print steel/titanium parts of the case, crown release system, and even parts of the movement. They cannot yet accurately print gears, but they are working with a new technology that should allow them to print both the movement bridges and gears. The current capabilities allow them to print steel and titanium at an accuracy of 25 microns. One watch takes approximately 6 months to manufacture, finish, assemble and test [90]**.**

Table 9 Barrelhand Project 1 - Technical Specifications [86]

Price:	$30,000 USD
Production time:	Approximately 6 months
Case:	• 44mm x 15mm • CNC machined Grade 5 Titanium • Black DLC Caseback • 5 ATM water resistance • AR coated sapphire crystal • Binder Jet steel lugs • Binder Jet steel crown release system
Strap:	• Hand stitched American Bison leather • DMLS steel lug insert • Binder Jet steel buckle

Digital Metal productions

Digital Metal is a HÖGANÄS GROUP company that offers a high precision metal binder jetting process. The Digital Metal printing takes place at room temperature in a build box that does not require any protective atmosphere. No supports are needed, since no melting takes place during printing. The surrounding powder provides enough support, which facilitates depowdering and reduces the need for post treatment. When the 3D printed components are taken out of the powder bed, all loose powder is removed and reused. After the depowdering, there is the sintering where the printed components are sintered to gain density and correct material properties following existing standards. Printing and heat treatment are separate processes, allowing for a wide selection of materials. Digital Metal offers a unique combination as it provides high precision details, fine surfaces, print tolerances, and high productivity of multiple parts in a single print that be either uniform or customised. To improve the surface quality of the parts, they are used some treatment post-processing like peening, blasting, and tumbling, that can reach an average of Ra 3.0 µm. The superfinishing process can reach a roughness of Ra 1.0 µm [15]. Digital metal high precision binder jetting uses advanced steel powders and various superalloys, as main materials. One of the major clients of this company is Montford watches (Figure 58), which is the first Swiss Made brand with 3D printed stainless steel dial. Digital metal high precision binder jetting allows Montfort to design unique and complicated dials, previously unproducible.

Figure 58: Montford Strata James model [16]

Figure 59 Mont Fort 3D-Printed dial [74]

The dials of the watches are made of super stainless steel; this gaseous carbo-nitriding technology is unparalleled in its flexibility, hardening performance and anti-corrosive properties. By diffusing at low temperature both nitrogen and carbon into the surface of the material, a layer is formed with a case depth of approximately 0.04 mm with a surface hardness around 1200 HV (Hardness Vickers scale). The treated steel is 8 times harder than standard steel improving drastically the resistance to scratches. Diamond Like Carbon (DLC) coating that Montfort uses is not new to the watch industry. DLC is an amorphous coating of Carbon atoms which has impressive tribology and hardness properties. DLC generally has a hardness between 1500-4000 HV. This Black DLC has a hardness of about 1500-18000 HV [17].

3.6. Other applications

Synchronos Alpha

An interesting project have been launched by Brad Balzer, the founder of Synchronos: the Synchronos Alpha.
The purpose of this project is to create a metal wristwatch, that is different from one people and another; the idea is that we have the customization of our watch depending on our arm (the movement of Alpha is not made by 3D printing, only the frame has been done by it).
They send the kit to do a 3D scan of our arm and after they get it, they use the Synchronos software; this program uses the scan to create a watch that fit exactly on you.
Unfortunately, this project needed a fundraiser to be launched on the market, but it was not so successful.

Figure 60 Syncronos Alpha

Lo scienzato Luminor

Lo Scienzato Luminor 1950 Tourbillon GMT Titanio PAM578, which is unique for its lightweight titanium case made by a high tech, 3D printing technique. The result is a case with a hollow interior that weighs less than 100 grammes, despite being 47 mm in diameter. Its lightness is helped by the fact that skeletonised bridges and base plate of the movement are also titanium, even though they are manufactured via traditional machining.

Figure 61 Lo Scienzato Luminor 1950 Tourbillon GMT Titanio PAM578

3.7. Summary

The two following tables summarize the previous study about Additive Manufacturing technologies in the watch industry, and also the Ceramic Injection Moulding ones. The Table 10 shows metal and ceramic applications that have been analysed and the Table 11 shows the polymer ones.

Table 10 Classification about metal and ceramic applications

METAL AND CERAMIC APPLICATIONS				
Watch company	**Watch model**	**Technology**	**Material**	**Post-processing and surface finishing**
Swatch Group	Rado’s model in grey ceramic	CIM	Grey ceramic	• Sandblasting • High-gloss polishing
	Rado’s model with grey/brown high tech polished plasma ceramic case		White ceramic	Plasma high-tech
	Rado’s model with features polished plasma CIM cases available in grey, blue, green or brown		Colourful ceramic	-
	Omega’s Seamaster Planet Ocean Big Blue		Blue zirconia ceramic	-
	Omega’s Speedmaster Racing model		Zirconia-based powder	Plasma treatment for precision laser engraving
TAG Heuer SA	TAG Heuer’s Carrera Heuer 01		Black ceramic	Micro-blasting on ceramic

Watch company	**Watch model**	**Technology**	**Material**	**Post-processing and surface finishing**
Hublot SA	Hublot's Magic Gold	CIM	"Magic Gold" alloy	-
	Hublot's new ceramic 'Click Italia Independent' womens luxury watch		Zirconium oxide ceramic material	Polishing on (zirconia oxide) ceramic
Seiko Watches	The limited-edition Grand Seiko Spring Drive Chronograph GMT	CIM/MIM	• Zirconia ceramic outer case • Titanium inner case	Mirror polish finishing on ceramic
Rolex	Rolex's Yacht-Master	Cerachrom process	Black ceramic	Polishing and sandblasting on ceramic
Uhrenmanufaktur Lehmann	Lehmann Schramberg's Intemporal Keramik	CIM	Dark ceramic	-
Royal College of Arts, London	Venus Concept Watch 1.0	SLM	• Stainless steel • Titanium	-
Hoptroff Watches	Watch case of 18K gold	SLM	Gold	-
Holthinrichs Watches	Holthinrichs Ornament 1 watch	BJ	• Stainless steel 316L • Titanium	Hand filing and polishing
Barrelhand	Barrelhand Project 1	BJ/DMLS	• Titanium • Steel	-

Watch company	Watch model	Technology	Material	Post-processing and surface finishing
Montford watches and Digital Metal	Montford Strata James model	High precision BJ	Super stainless steel	- Gaseos carbo-nitriding technology - Diamond Like Carbon (DLC) coating
Synchronos Alpha	Synchronos Alpha	-	- Stainless steel - Onyx - Gold - Rose Gold - Aluminum - Titanium	-
Panerai	Lo Scienzato Luminor 1950 Tourbillon GMT Titanio PAM578	-	Titanium	-

Table 11 Classification about polymer applications

POLYMER APPLICATIONS				
Watch company	**Watch model**	**Technology**	**Material**	**Post-processing and surface finishing**
Tourbillon Watch	Laimer Tourbillon	Material Extrusion	Polymer / PLA	-
	3D printed mechanical Clock with Anchor Escapement		PLA	-
ALB	Model ALB 000 «Balade au Brézéguet»	SLS	Polyamide	-
	Model ALB 100 «Secondes d’Eclipse»			
	Model ALB 200 «Promenade à Etretat»			
	Model ALB 110 «Vers le bout du monde»			

4. AM vs Conventional Technology in the watch industry

Introduction

“Although most of the brands in the watchmaking industry are defined by their heritage, it doesn’t mean that modern technology can’t help create a better watch” [26].

“Machinery like 3D printers, multi-axis milling and turning machines, they all allow watch manufacturers to do what wasn’t possible just 10 or 15 years ago. And that developmental pace is picking up. You can produce components that were unimaginable back then” [27].

“Watchmakers redefined and combined values of craftsmanship, luxury, and precision to create new meanings and values for mechanical watch technology; repositioned the mechanical watch as an identity and status marker” [28].

Additive Manufacturing (AM) technologies use revolutionary technology to create complex and very small shapes building a part layer by layer. Contrary to traditional techniques, where material is either removed via machining, drilling, or grinding techniques or casted into moulds, AM has a higher level of design freedom. It has also the ability to fabricate complex parts in one machine. Furthermore, by using some AM technologies, it is possible to obtain the final shape already from the component just 3D printed, reducing costs and times of production. To increase the surface quality, sometimes, are required some post processes that allow to achieve excellent values of surface roughness, that cannot be achieve with traditional technology or need a lot of and complex operations. Through these AM technologies it is possible to work with very different materials: from polymers, to ductile metals, to brittle materials like ceramics, to very luxury ones like gold. Since these technologies are not chip removal ones, in many cases the materials do not keep their initial properties, but during the treatments they can be increase their mechanical properties like strength or hardness. So, the Additive Manufacturing can guarantee the realization and production of the parts in the watch industry, since the main aspects that are required are:

1. High surface quality.
2. Resistance to scratch (obtainable by using some post processes that we have already seen).
3. Complex and original designs to make a product unique.
4. Polishing and blasting effects on our parts.
5. Luxury materials.

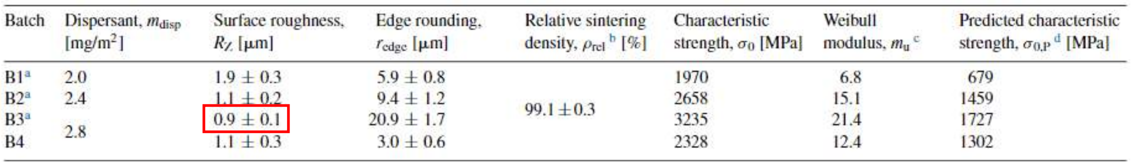
After this brief introduction, we want to go in depth on some points that we are talking about before and show some other reasons why the use of 3D printing could be interesting in spite of traditional technologies.

4.1. Surface quality

In this paragraph we have analysed the roughness which is obtained by using some specific Additive Manufacturing technologies and materials. We have analysed the main cases which can appear during the manufacture of a watch part and we have been already seen in the Chapter 3 in some applications. We have studied the Ceramic Injection Moulding of the ceramic, the Binder Jetting of stainless steel, the selective laser melting of the stainless steel and of gold, the material extrusion of PLA and the selective laser sintering of the polyamide. The following tables resume the values that we have founded in our researches.

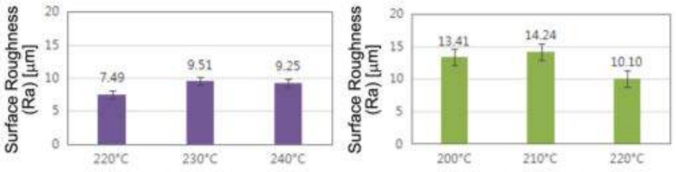
Technology	**Material**	**Process parameters**	**Final value of roughness [µm]**
CIM	Ceramic	-	0.9 ± 0.1 (after thermal debinding)

Table 12: Properties of sintered 3Y-TZP micro bending bars as a function of the amount of dispersant applied for feedstock formulation [30].

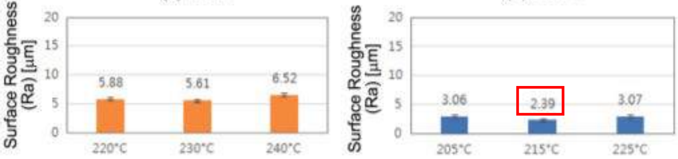


Batch	Dispersant, m_{disp} [mg/m^2]	Surface roughness, R_Z [µm]	Edge rounding, r_{edge} [µm]	Relative sintering density, ρ_{rel} ^{b} [%]	Characteristic strength, σ_0 [MPa]	Weibull modulus, m_u ^{c}	Predicted characteristic strength, $\sigma_{0,P}$ ^{d} [MPa]
B1^a	2.0	1.9 ± 0.3	5.9 ± 0.8	99.1 ±0.3	1970	6.8	679
B2^a	2.4	1.1 ± 0.2	9.4 ± 1.2		2658	15.1	1459
B3^a	2.8	0.9 ± 0.1	20.9 ± 1.7		3235	21.4	1727
B4		1.1 ± 0.3	3.0 ± 0.6		2328	12.4	1302

Technology	**Material**	**Process parameters**	**Final value of roughness [µm]**
Material extrusion	PLA	-	2.39 (without post processes)



(a) ABS (b) HIPS



(c) PETG (d) PLA

Figure 62: Comparisons of surface roughness for 3D printing temperature [83].

Technology	**Material**	**Process parameters**	**Final value of roughness [µm]**
SLM	Stainless steel	- layer thickness 20 µm - beam scan speed 900 mm/s - hatch spacing 100 µm - fibre laser with wavelength 1060-1100 nm - beam diameter of 100 µm - maximum power output of 195 W	12 (without post processes)

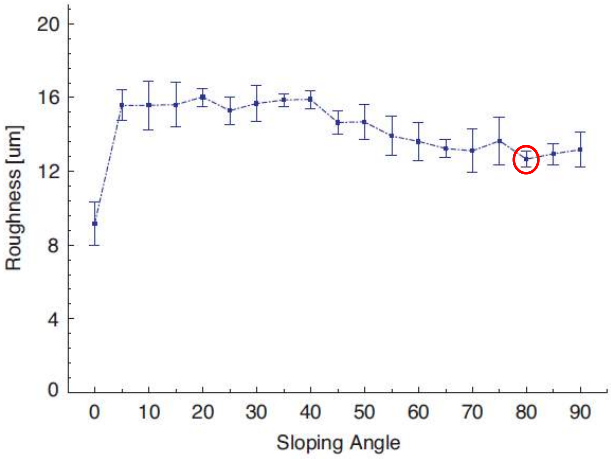
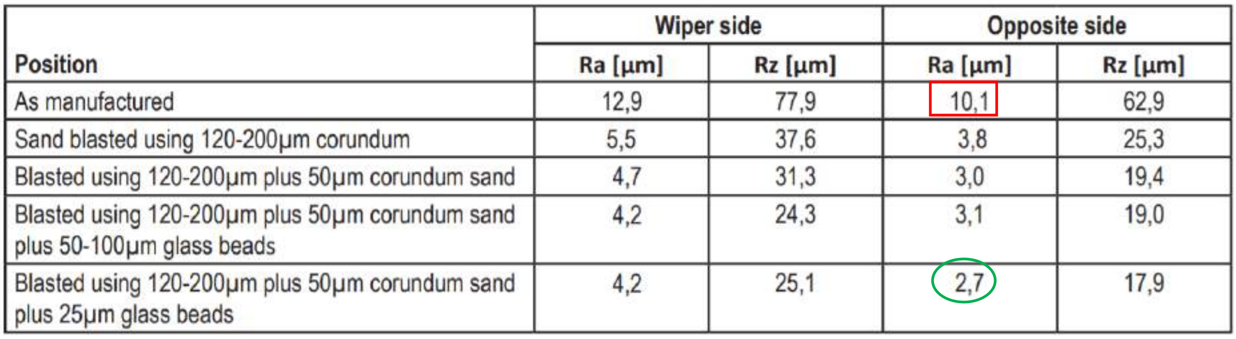


Figure 63: Experimental roughness at different sloping angle [82].

Technology	**Material**	**Process parameters**	**Final value of roughness [µm]**
SLM	Gold	- maximum power 100W - wavelength 1064 nm	10.1 (without post processes) 3.8 (after sand blasting) 2.7 (after 3 blasting post processes)

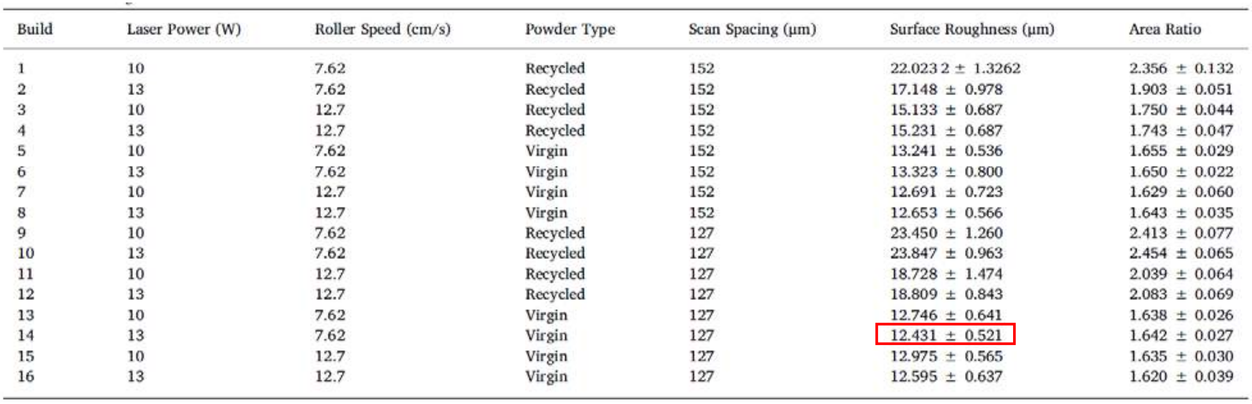
Table 13: Surface roughness which can be obtained with and without post-processes [84]



Position	Wiper side		Opposite side	
	Ra [µm]	Rz [µm]	Ra [µm]	Rz [µm]
As manufactured	12,9	77,9	10,1	62,9
Sand blasted using 120-200µm corundum	5,5	37,6	3,8	25,3
Blasted using 120-200µm plus 50µm corundum sand	4,7	31,3	3,0	19,4
Blasted using 120-200µm plus 50µm corundum sand plus 50-100µm glass beads	4,2	24,3	3,1	19,0
Blasted using 120-200µm plus 50µm corundum sand plus 25µm glass beads	4,2	25,1	2,7	17,9

Technology	Material	Process parameters	Final value of roughness [µm]
SLS	Polyamide	- scan speed 1676 mm/s - layer thickness 0.100 mm - bed temperature 166°C - spot size 0.450 mm - scan count 1 - hatch length 0.15 mm	12.43 (without post processes)

Table 14: Value of the parameters which are obtained [84].



Build	Laser Power (W)	Roller Speed (cm/s)	Powder Type	Scan Spacing (µm)	Surface Roughness (µm)	Area Ratio
1	10	7.62	Recycled	152	22.023 2 ± 1.3262	2.356 ± 0.132
2	13	7.62	Recycled	152	17.148 ± 0.978	1.903 ± 0.051
3	10	12.7	Recycled	152	15.133 ± 0.687	1.750 ± 0.044
4	13	12.7	Recycled	152	15.231 ± 0.687	1.743 ± 0.047
5	10	7.62	Virgin	152	13.241 ± 0.536	1.655 ± 0.029
6	13	7.62	Virgin	152	13.323 ± 0.800	1.650 ± 0.022
7	10	12.7	Virgin	152	12.691 ± 0.723	1.629 ± 0.060
8	13	12.7	Virgin	152	12.653 ± 0.566	1.643 ± 0.035
9	10	7.62	Recycled	127	23.450 ± 1.260	2.413 ± 0.077
10	13	7.62	Recycled	127	23.847 ± 0.963	2.454 ± 0.065
11	10	12.7	Recycled	127	18.728 ± 1.474	2.039 ± 0.064
12	13	12.7	Recycled	127	18.809 ± 0.843	2.083 ± 0.069
13	10	7.62	Virgin	127	12.746 ± 0.641	1.638 ± 0.026
14	13	7.62	Virgin	127	12.431 ± 0.521	1.642 ± 0.027
15	10	12.7	Virgin	127	12.975 ± 0.565	1.635 ± 0.030
16	13	12.7	Virgin	127	12.595 ± 0.637	1.620 ± 0.039

Technology	Material	Process parameters	Final value of roughness [µm]
Binder jetting	Stainless steel	-	6.3 ± 0.4 (without post processes) 4.3 ± 0.8 (after blasting) 0.88 ± 0.45 (after superfinishing)

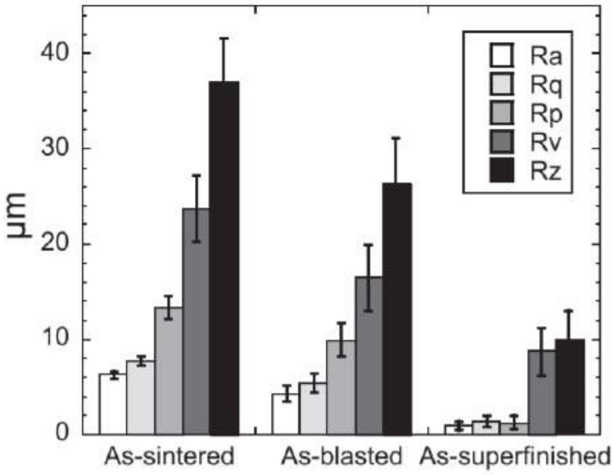


Figure 64: Surface texture parameters of the BJ printed 316L with different surface finishing processes [85].

Comparison

The Table 15 resumes the previous considerations and compares them with the roughness which can be obtained by using traditional processes [UNIM 36].

Table 15 Resuming of all collected data

AM technology	**Material / alloy**	**Max surface roughness [µm]** (without post processes, at the first wipe)	**Min surface roughness [µm]** (with post processes)	**Traditional process surface roughness [UNIM 36]**
Ceramic injection moulding	Ceramic	-	0.9 ± 0.1	Smooth surface obtained by machine or hand operation
Material extrusion	PLA	2.39	-	Smooth surface obtained by machine or hand operation
Selective laser melting	Stainless steel	12	-	Roughing surface obtained by machine or hand operation
Selective laser melting	Gold	10.1	2.7	Smooth surface obtained by machine or hand operation
Selective laser sintering	Polyamide	12.43 ± 0.52	-	Roughing surface obtained by machine or hand operation
Binder jetting	Stainless steel	6.3 ± 0.4	0.88 ± 0.45	Smooth surface obtained by machine or hand operation

4.2. Costs and Time

Another observation that can be made considering the differences between AM technologies and chip removal ones is about the loss of material. In fact, when we use chip removal processes, the material which has been removed it cannot be reuse in many cases. So, we have a lot of waste of material and this fact causes necessarily an increase of the costs, particularly in the cases in which we have luxury materials that are usually used to make watches. This problem doesn’t appear when we use AM technologies, in fact the powder that doesn’t take part to the building of our component can be reuse for another work and where we have some support structures they are made, usually, by a specific material which in it could be different from the main one which is used for the realization of the part. Regarding the costs in the watch industry by using Additive Manufacturing technologies, we want to observe what is the relationship between the costs, the times of production and the volumes of production. Figure 65 summarises the results of lead time for each quantity-based scenario and many manufacturing methods. The most time-consuming method for quantities up to 500 pieces is injection moulding. The significant difference is attributed to the time that a mould requires to be constructed. For a mould to be constructed by a traditional method, it needs around 2-3 months, which is a significant amount of time, especially when injection moulding is compared with toolless manufacturing methods, such as AM. If the product examined had its mould already fabricated and ready for use, it would need approximately 360 times less time to produce 1-10 pieces and 25 times less time for the production of 500 pieces. As depicted in the zoom in Figure 65, injection moulding without the mould construction takes the lowest value for any production volume and compared to any other manufacturing method. This is seconded by AM using SLA and SLS for the volume of one product. For the production of one product, FDM shows the longest lead time, after injection moulding with mould construction [56].

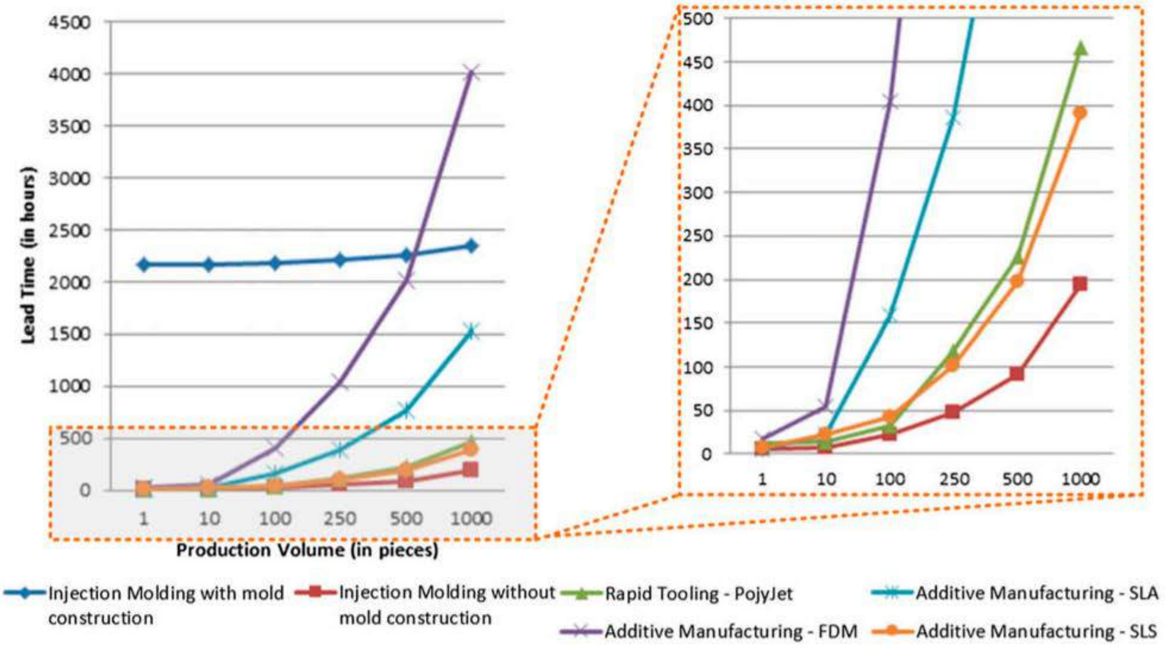


Figure 65: Lead time vs productivity [56].

Figure 66 illustrates the results for the total production cost that is calculated for each scenario and each manufacturing method.

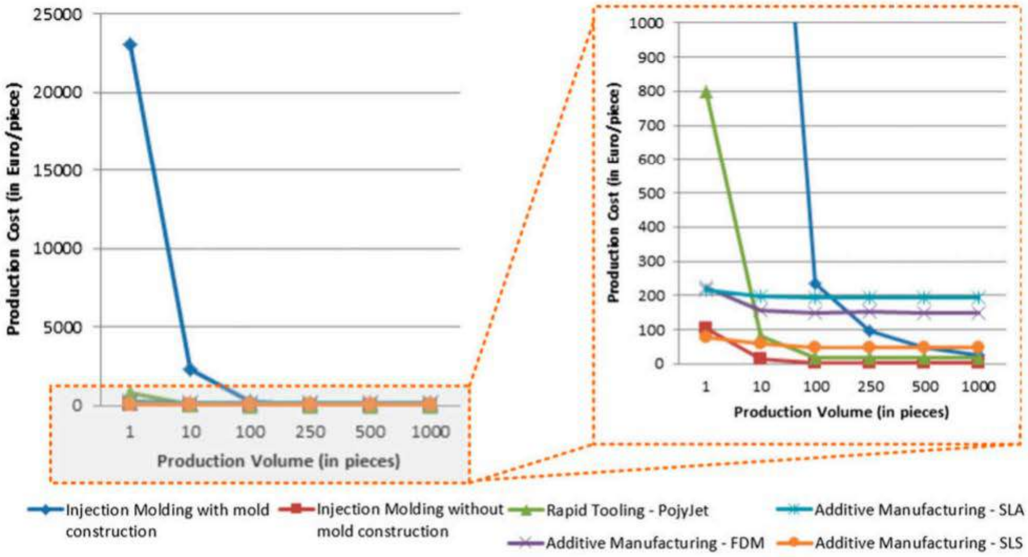


Figure 66: Production cost vs productivity [56].

For production volumes of 1-100 units, the most expensive method is injection moulding with mould construction. This is reasonable, since the fabrication of a hard tool, i.e. a steel mould, costs usually tens of k€ [56]. We can also observe in Figure 67 that in conventional manufacturing, increasing complexity and/or customization leads to increased cost. With additive manufacturing, complexity or customization becomes free [56].

How we can see there is a break-even cost point between conventional and additive manufacturing when comparing cost per part and production volume. 3D printing is likely to be more competitive than conventional manufacturing when it comes to fabricating products with higher levels of complexity, customization, or a combination of both. Additive manufacturing enables product agility, which is required in a field like the watch industry. Small custom parts such as watches can be produced in high volumes today using custom tooling (e.g., moulds for CIM) produced through additive manufacturing. More high-volume product opportunities will be realized as additive processes evolve to have higher production rates through larger build volumes, faster build speeds, or continuous processes [56].

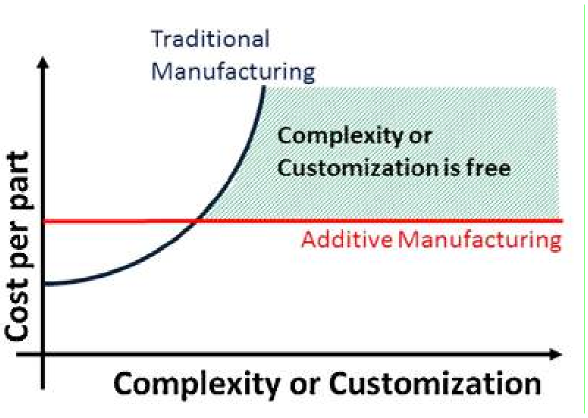


Figure 67: Cost per part vs customization [56].

4.3.Machinability of ceramic

Talking about ceramic we must mention its low machinability, in fact as explain in [68] conventional machining can be a cost-effective method of making complex-shaped ceramic. This is caused by its low machinability, and so we need particular processes and tools (for instance diamond tooling, ultrasonic, waterjet and EDM) [69][70]. This concept is underlined in [69] where is explained that the optimum process for ceramic component will use a combination of several processes. The cost of ceramic can be compared by most valuable metals, because basically the raw material that is used to produce ceramic is a cheap material, but the process to produce the final shape is complex and high costs. Thanks to additive manufacturing we can produce complex shape without the mean of a mould, and so we can drop the costs.

4.4. Prototyping

Additive manufacturing could be preferred in a pre-production process, where a company is still in an early phase of product's engineering without having a solid model to analyse and improve but only some 3D-CAD concept. In fact, manufacturing such small components with particular shapes, just for testing the current product development, could be extremely costly, and could lead to increasing the final price of a watch. This cheaper way is mostly used and highlight by start-ups, that do not have a high budget either the know-how typical of the historical brands.

An example is Barrelhand (we have talked about them at page 51) , a company that thanks to 3D-printing manage to test and improve by multiple iterations of prototypes his Project 1, without needing to invest lot of money [14].

Each Barrelhand project is prototyped using the latest in SLA, MJM (Multi-jet Modelling) and MBJ 3D printing technology [86]. During the prototyping phase one of the most expansive part, it would have been the sapphire crystal, due to the complex shape of the piece it would be needed to carve out an entire block of sapphire crystal. Instead, the part was realized by additive manufacturing, with a material known as "Watershed XC" (engineering grade ABS-like photopolymer) and polished for guarantee a good optical clarity, this makes the operation cheaper Figure 68 [75].

Figure 68 3D-Printed crystal: before and after polishing [75]

Thanks to these solutions Barrelhand manage to create parts at nearly tenth of the cost of traditional manufacturing. By minimizing prototyping costs and machine time, projects can be completed with maximum value to the end product [86].

4.5. Environment

One of the major technologies that are going to be important in AM development in the next few years is its environmental friendliness through low material wastes, no tooling required and the possibility to produce different parts at a time. Design for Additive Manufacturing gives advantage of the unique design freedom and allows superior functional integration and part consolidation in the manufacturing. It can reduce significant resources and energy consumptions which leads to less pollutant emissions in the upstream. Instead of allowing all the products and materials to degrade and be wasted, they should be in the process of recoverable, reusable, and recyclable which help us to enable the next lifecycle of the products. AM can reduce the "cradle-to-gate" environmental footprints of component manufacturing through avoidance of the tools, dies, and materials scrap associated with conventional manufacturing processes [80][81].The New design solutions that involve additive manufacturing (AM) provide opportunities for product life extension, reuse, and recovery in the AM Industry itself.

Reduces waste

AM major advantage being that manufacturers can print parts on demand. This will help to reduce the need for tooling and reduces the amount of material required to produce any components. Any solid metals require forming and milling, both processes that require large amounts of energy and creates lot of material waste. AM enables components to be printed on demand, no finished product goes unsold, so there is no over-production, and it helps to reduce waste.

Reduces emissions

AM enables shorter, more localised supply chains, therefore significantly reducing the amount of freight journeys and weight required to transport industrial materials that can be printed either on-premises with the right equipment, or much nearer to the factory. The study calculations show that 3D Printing contains the potential to reduce costs by 170–593 billion US $, the total primary energy supply by 2.54 - 9.30 EJ (1 EJ = 10^{18} J) and CO_2 emissions by 130.5 - 525.5 Mt (1 Mt = 1000 kg) by 2025 [79].

Still lot of research are needed to improve the technological capacities of 3D Printing. Research on sustainability implications of 3D Printing from a Life Cycle Analysis perspective, a micro-economic perspective or a bottom-up approach. Research is also needed to understand the crucial determinants of direct and indirect energy use and CO_2 emissions in 3D Printing and how these can be reduced on a technological level and on a societal scale [79]. The production rate of 3D Printing represents a central aspect in research as it is directly connected to the applicable size of production volumes of any required part. Faster 3D Printing processes can be applicable to larger production series in an economically feasible manner and offer significant sustainability potentials.

5. Conclusions and Future Improvements

This is the last chapter of our work, in which we want to gather all the information that we have founded and the conclusions that we have been able to achieve concerned the Additive Manufacturing in the watch industry. Thanks to these results we have been also able to make some considerations about future developments.

First of all, have been analysed some of the additive manufacturing technologies that are used in the watch field and the chemical and physics characteristics of the stainless steel, titanium, gold, ceramic, and nylon, some of the main materials which are used for the production of the watches. In particular, we had to focalize our attention on the processes of Material Extrusion, Selective Laser Sintering (SLS) and Stereolithography (SLA) which regarding the production of plastic and polymer watches. And finally, we have decided to describe the processes of Laser Melting (SLM) and Binder Jetting (BJ) that are the main processes that are used for the manufacturing of the metal watches (Table 1). We have also analysed the processes of the Powder Injection Moulding for the production of ceramic watches, whose main technology which is used is the Ceramic Injection Moulding (CIM) (Appendix).

We have seen that Ceramic Injection Moulding is widely used for the manufacturing of the watches by using zirconia ceramics in all of its colourful shapes. Many watchmakers use the Ceramic Injection Moulding for their watch cases, in full or in part, for bracelets and other components largely due to the allure of highly polished or striking matt ceramics, with their extreme hardness offering superior scratch resistance. Ceramic have also the properties of the cool touch and to be hypoallergenic. The CIM parts can be also polished to give a satin finish or sandblasted to give a matt finish: these are the two main post processes that have been used by the watchmakers to give special and aesthetic characteristics to their products. Swatch Group is one of the main companies which uses CIM for the production of the watches, for example its ceramic Rado collection has many parts of the watches that are entirely made by using this technology. Ceramic is one of the hardest class of materials, so it is resistant to scratches. It also will not corrode or cause allergenic reaction, because it is inert material. On the other hand, due to high hardness we must consider that it is fragile material, so we need some improvement to avoid fragility. Ceramic has low toughness, high hardness, and high fragility so we have many problems to machine it. Ceramic is used to produce watch case, bezel and bracelet and can be produced in different kind of colours, that is an interesting feature for the customers tastes.

The Selective Laser Melting and the Selective Laser Sintering are two very similar technologies that use metal, ceramic and polymer powders, but in the watch field are widely used for the manufacturing of the metal watch parts. In the case of SLM the powders are fully melted, so they go for fast solidification which leads to shrinkage and this generates residual stress which can be relieved by annealing. The SLM is able to produce gold watch parts, but we have to consider that, since the gold has a very high reflectivity, we have to be able to control this characteristic in order to allow the melting of the powder. In order to reduce its reflectivity are applied some solutions like powder treatments and modifications of the alloying elements. The Hotproff watch, for example, develops a 18k watch case by using SLM process and after fine-tuning their design process, they were able to move from ruttier gold watch casings to something a little more refined. Gold may be used to make watch cases, bezels, bracelets, and the most precious parts of the movement. Nowadays the movement

of the parts cannot be produced by 3D printing, because we need a precision that is not still reached with this type of technology, but it could be a future improvement.
The Binder Jetting is used for the fabrications of metal watch parts, but it is also able to manage ceramic materials. This technology always needs post-processes that sometimes take longer time than the actual printing and may incur significant costs. For example, we have seen that the Digital Metal company offers a high precision metal binder jetting process and collaborates with Montford watches company to create very unique stainless steel watch parts. Thanks to the high corrosive resistance and the high hardness a stainless steel's surface maintains its beauty for a long time even in a non-ideal environment, so is widely used material in the watch field. Instead, titanium is used in watch industry mainly because of its property to be the most biocompatible metal and it is also one of the most corrosive resistant common metal. Compared to steel is lighter but it is also more expensive 4-5 times more than stainless steel and because of his lower hardness it is also easier to scratch. For example, Barrelhand creates, by using metal binder jetting, a titanium watch case, characterised by a revolutionary clock mechanism: the current hour is read with a jumping mechanism at the top of the dial, and the minutes display is located at what would normally be 6:00.
For the production of the plastic parts of a watch it is also used the Stereolithography in which the final step of the process is, in many cases, the curing; this treatment improves the strength and gives stability to the fabricated part. Material extrusions is also used for plastic watch parts or prototyping, and the main component of the watch that we can produce with polymer material is the strap. Nylon, also called Polyamide (PA) is a widely used polymer in the additive manufacturing sector, in fact it has many advantages like, well fitting, durable and lightweight, it is affordable, and it presents a variety of colours and styles, it is also ideal for metal allergic people. The Material Extrusion allows to create very free shape, for example it is used by the artist Christoph Laimer for creating his Tourbillon collection: thanks to the flexibility of this technology, he was able to invent unique plastic watches.

The Additive Manufacturing (AM) technologies use revolutionary technologies to create complex and very small shapes building a part layer by layer. Contrary to traditional techniques, where material is either removed via machining, drilling, or grinding techniques or casted into moulds, AM has a higher level of design freedom. When we use chip removal processes we have a lot of waste of material and this fact causes necessarily an increase of the costs, particularly in the cases in which we have luxury materials that are usually used to make watches. This problem doesn't appear when we use AM technologies, in fact the powder that doesn't take part to the building of our component can be used for another work and where we have some support structures they are made, usually, by a specific material which in it could be different from the main one which is used for the realization of the part. Additive manufacturing enables product agility, which is required in a field like the watch industry. To increase the surface quality, sometimes, are required some post processes that allow to achieve excellent values of surface roughness, that cannot be achieve with traditional technology or need a lot of and complex operations. From the analysis of the surface roughness, we have seen that for both Ceramic Injection Moulding and Binder Jetting we can obtain very high levels of surface quality and roughness and these excellent characteristics can be achieved by using traditional technologies only after many and many passes and by using very advanced tools and machines. Regarding the low machinability of the ceramic, it needs particular processes and tools like diamond tooling, ultrasonic, waterjet and EDM. It would be very interesting to go in depth with AM because thanks to it we can produce complex shape without the mean of a mould or particular tools or processes, and so we can cut the costs.

Another characteristic of the AM technologies is that they give the possibility to realize a lot of prototypes without spending much money. We have also seen that the Additive Manufacturing technologies reduce significant resources and energy consumptions leading to less pollutant emissions. They can guarantee reducing of waste and emissions.

5.1. Gold improvements

Thanks to the addition of different alloying elements, we can create different colour of our gold pieces. We are talking about white, red and pink gold for example. As we have mentioned in the introduction of gold (page 24), were taken depth studies only in 18kt gold and what we expected from the future is that more studies have to be done also on the other type of gold, in order to give to the customer a higher possibility of choices. About this we want to say that the production of this type of material is actually present, but what we want to see in future is a more detailed study about this so as we can exploit as best as possible them.

Previously we have said that nowadays we can't produce internal component of the watch, because with 3D printing, we are not able to create precious part like the gears of the movement. It is interesting to go in depth in this, because for instance gold as high wear resistance (good for element that crawl on each other), and also high electrical conductivity that in modern smartwatches can be utilized for some small part in the electronics circuits.

5.2. Ceramic improvements

In general, Additive Manufacturing (AM) has the potential to disrupt the ceramic industry by offering new opportunities to manufacture advanced ceramic components without the need for expensive tooling, thereby reducing production costs and lead times and increasing design freedom. Selecting the correct AM process for a given application not only depends on the requirements in terms of density, surface finish, size, and geometrical complexity of the part, but also on the nature of the particular ceramic to be processed. The two graphs in Figure 69 show that AM is more economical than injection moulding when working with small production volumes due to the lack of economies of scale and/or when manufacturing highly complex parts since hard ware and tooling modifications are not required when increasing part complexity [31].

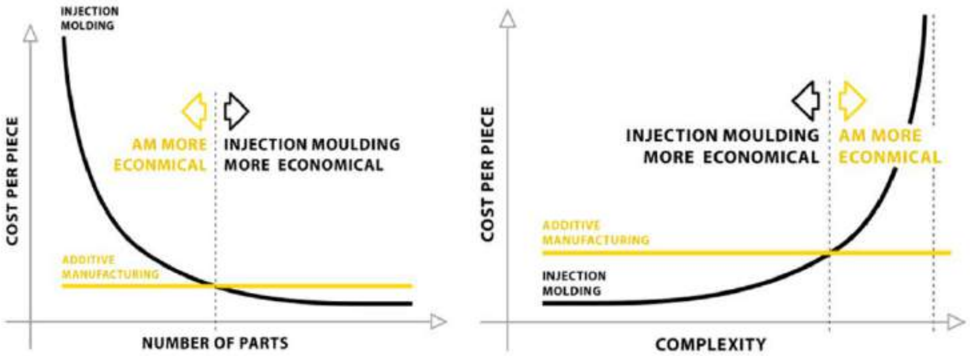


Figure 69:[31].

So as a future development, we intend to expand research regarding the processing of ceramics, a material widely used in the watch industry, so that it can also be well worked through additive manufacturing technologies, obtaining results comparable to those relating to ceramic injection moulding.

The paper [43] demonstrated that stereolithography-based additive manufacturing showed a great possibility for preparing gray-colored SiC ceramic structures. However, there are still many challenges need to overcome, such as how to improve the curing ability of gray-colored SiC ceramics. We want to be able to work with SiC, because it is the hardest and lighter ceramic material in the market. As shown in [44] more studies about this are needed, because the increase of colorant content has a beneficial effect on the excess cure width, so if we managed better the depth cure we can achieve different ceramic colourful pieces without any kind of problems. The main research improvements have to be applied on the creation of different colours ceramics, because for the properties of the powder and material as we seen thanks to zirconia in [4], we have reached good characteristic that are enough for the production of a watch. Even though other improvements in this way can be applied to decrease more and more the fragility, that is the weakness for ceramics. As shown in [45] another thinks that we have to take in account is the residual stresses caused by thermal gradients, that for instance can be reduced by addition of zirconia, as shown in [35], but many research have to be done in this field; other way to reduce this problem can be preheating the powder beds.

5.3. Environment and Toxicological hazards

Last thing that we want to talk about in future improvements is that there still much work to be done to meet today’s environmental and global challenges, but the promise and potential exists in the AM Industry If more global leaders and engineers get together to learn and understand the new tools, and bring them into business in a meaningful way, we have an opportunity to create a step change in efficiency across the manufacturing economy.

The toxicological and environmental hazards as well as safety issues of AM are not well known at present and should be the focus of further research [78]. Potential health problems can be found in severe eye and skin irritation as well as allergic skin reactions and inhalation risks. Therefore, proper dust collection and air ventilation as well as the use of protective gloves and safety glasses and masks is highly recommended [78].

Overview over 3D print technologies

Source and Hazards

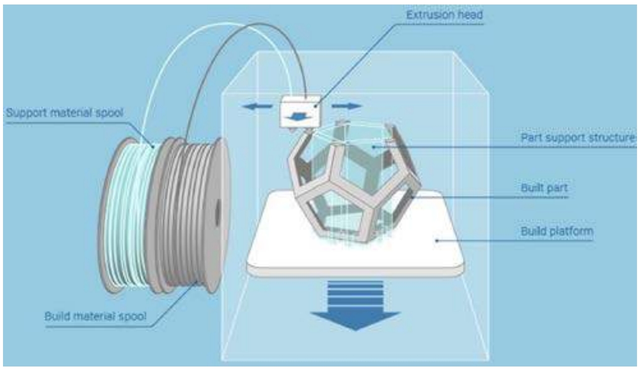


Figure 70 Fused Deposition Modeling (FDM) [76]

Heated nozzle powder:

- ultrafine particles
- VOC emissions
- explosion
- fire burns

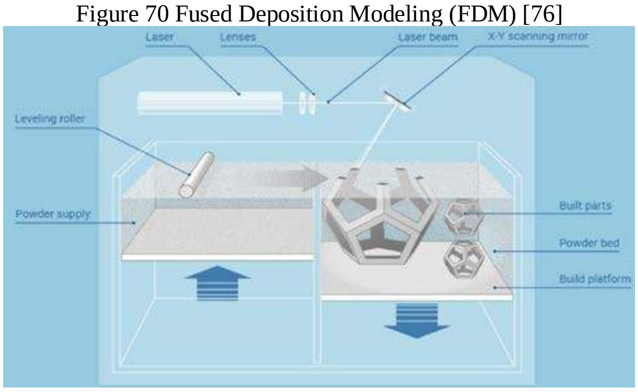


Figure 71 Selective Laser Sintering (SLS) [76]

CO_2 laser:

- ultrafine particles
- explosion
- fire

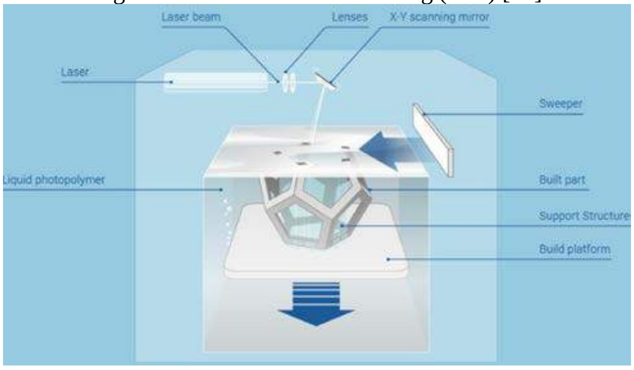


Figure 72 Stereolithography (SLA) [76]

UV laser or projector:

- toxicity of compounds
- solvents used to wash unreacted material

5.4. Final Considerations

Concluding, the Additive Manufacturing can guarantee the realization and production of the parts in the watch industry, whose the main characteristic must be: having an high surface quality and the resistance to scratch (obtainable by using some post processes), having complex and original designs characterised by polishing and blasting effects on the parts, and they have to be made by luxury materials. We know that AM technologies have already some limitations in the watch industry, but we also know which are the aspects that can be improved and, believing in the scientific progress, we will be able to achieve our goals.

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Appendix

Powder Injection Moulding: metal and ceramics components

At the end of our work, we want to show something about a technology that is a state of the art for the creation of ceramic part; as we can see in the paragraph 3.1Applications of the CIM, there are a lot of uses in the watch industry for producing ceramic parts, so we put it to underlines the difference that there is between the production of wristwatches thanks to AM and CIM.

Powder injection moulding (PIM) has emerged as a viable method of producing complex shaped parts at a competitive cost. The PIM process uses a combination of powder metallurgy and plastic injection moulding technologies to produce net-shape metal, ceramic or hard material parts and is comprised of feedstock preparation, injection moulding, debinding and sintering as shown in Figure 73. Powder injection moulding is an attractive process when the following component features apply: thickness ranging from 0.2 to 20 mm, corner radius greater than 0.075 mm, mass ranging from 0.02 to 1000 g, moderate levels of shape complexity and smooth surfaces. The typical range of tolerances is between 0.1 and 1 mm. The technology is usually used for complex components made of metal or ceramics in mass production [2].

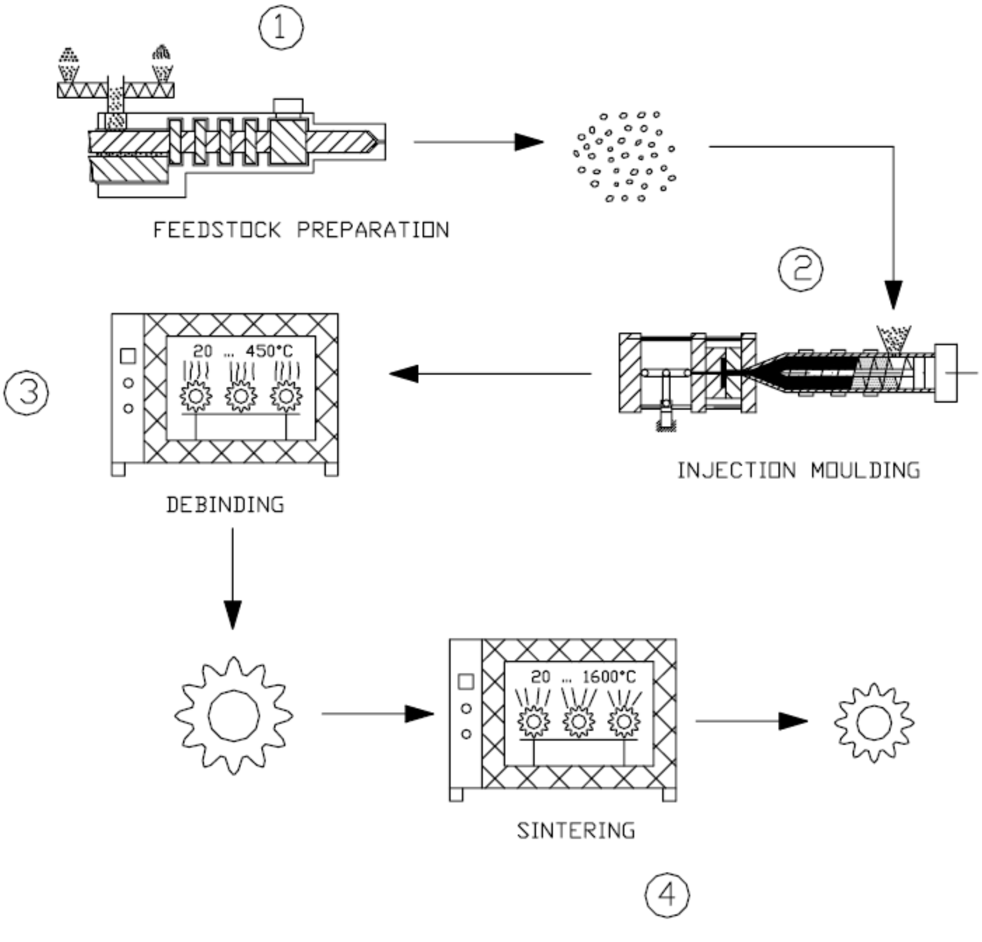

Figure 73: The four main steps of PIM [2]

How PIM works: Metal Injection Moulding (MIM) and Ceramic Injection Moulding (CIM)

All versions of the Metal Injection Moulding (MIM) process consist of four steps: mixing, moulding, debinding and sintering. These steps can be followed by secondary operations, such as drilling and tapping, to produce a part whose dimensions are as specified on the blueprint. In many cases, the final finishing operations include a surface finishing step such as bluing or plating [4].

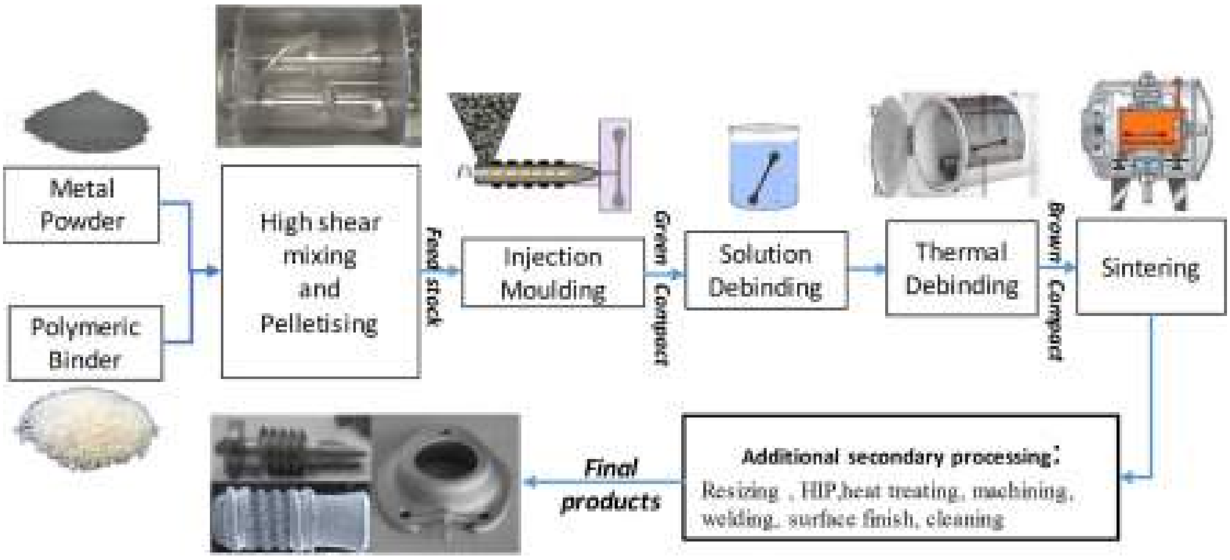

Figure 74: Metal Injection Moulding process [37]

In mixing, fine metal powders, usually less than 10 μm are combined with a thermoplastic binder [4]. The injection moulding of metal powder-binder mixtures consists of heating a metal and injecting it, under pressure, into a mould. For ferrous materials, the shape-making ability of injection moulding is greater than for any other process outside of expensive machining operations [4].

After moulding, the binder is removed. In one common method, the part is heated under vacuum, decomposing, and vaporizing the binder. Carefully determined temperature and vacuum profiles must be used, as too rapid vaporization of the binder will crack the part. A variation of this process involves debinding in air, which oxidizes the metal powders [4].

The final step is sintering, where the part is heated close to the melting point. Both vacuum and hydrogen sintering are employed. The part densifies as it sinters, markedly reducing the void volume and part size [4].

Ceramics are also commercially produced by the injection moulding process. Experimental work has been carried out on carbides and composites as well. The differences between the ceramic and metal processes are in detail. Ceramic parts can be debound and sintered in air. Ceramic-filled binders have a lower thermal conductivity than their metal counterparts. This makes it easier to fill the mould and should permit a greater range of wall thicknesses and better tolerance than is achievable in metal [4].

We need to have a homogeneous distribution of powder and binder to avoid segregation of feedstock components, that will cause visual defects, excessive porosity, warpage, and cracks [37].

Many watchmakers now use the Ceramic Injection Moulding (CIM) for their watch cases, in full or in part, as well as for bracelets and other components largely due to the allure of highly polished or striking matt ceramics, with their extreme hardness offering superior scratch resistance. The cool touch and hypoallergenic properties of ceramics are of course further positive considerations. Ceramic watch components have been produced using ultrafine tetragonal zirconia powders, although other types of ceramic powders, including silicon nitride, titanium nitride and boron carbide, have also been used [1]. The ceramic powders are blended with a binder before being homogenised and granulated to produce the feedstock for injection moulding to net shape. Following injection moulding the components then go through binder removal stages. The solvent debinding process has been widely adopted in the CIM sector where a portion of the binder is chemically removed using solvents such as acetone, trichloroethane or heptane. The open porosity created after solvent debinding allows the degraded products to diffuse easily to the surface of the parts. After debinding, the ceramic parts are sintered in dedicated sintering furnaces at temperatures around 1450°C. The sintered CIM parts can be polished to give a satin finish or sandblasted to give a matt finish. Whilst black zirconia parts have become standard for many CIM watch parts, higher end watch producers have begun turning their attention in recent years to incorporating other colours and tones such as red, blue, orange, white, grey and brown. For coloured CIM zirconia parts, the material has to be pigmented with mixtures of several transition metal oxides such as iron, cobalt, nickel, manganese and chromium. The key to the selection of colouring pigments is that they must survive the high sintering temperature without evaporating or melting [1].