Why Should We Direct 3D Print Jewelry? A Comparison between Two Thoughts: Today and Tomorrow

AUTHORS

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1. INTRODUCTION

Production processes in the gold jewelry industry have remained basically unchanged for hundreds of years without actual revolutions in the manner of creating jewelry. Only in recent decades have some of the technological inventions of the twentieth century, including electroforming, CNC machining, rapid prototyping, laser soldering and metal injection molding (MIM), been adopted by the gold industry and integrated into the production process, leading to incisive innovations.

Sometimes these changes were introduced as improvements to the old, established manufacturing processes, which remain widely followed to this day thanks to their undoubted effectiveness, without leading to the development of brand-new production routes. In other cases, the use of technological innovation has led to the complete revolution of production processes due to the adoption of entirely different and original manufacturing mechanisms, basically unthinkable just a few decades ago.

Among the latter techniques, the ones capable of completely overturning the up-to-now known rules of production, there is selective laser melting (SLM™). Compared to classic jewelry manufacturing techniques, selective laser melting is an extremely young technology that was born from a collaboration between the Fraunhofer Institute of Aachen, Germany, and the F&S Stereolithographietechnick GmbH in 1995. The commercial distribution of the first printers began a few years later, in 2000, in collaboration with MCP HEK GmbH, then renamed SLM™ Solution GmbH, and currently sharing the technology with Realizer GmbH of Dr. Matthias Fockele. The SLM technique differs from selective laser sintering (SLS™) since the former allows the complete melting of the particles by the laser beam, whereas the latter consists of surface welding by means of the temperature.

Unlike laser melting, lost-wax casting—the leading manufacturing procedure in the gold sector—boasts ancient origins. Its earliest employment for serial production dates back to the early Bronze Age (3000–3500 BC). Since the early days of this technique, the production of artifacts has always required a model to reproduce, separately shaped in hand-moldable material, establishing from the outset the impossibility of the direct construction of the objects as designed by the artist or by the craftsman. Although there are several lost-wax casting techniques applied to jewelry production, each one of them implies a considerable complexity in the process due to the production of rubber molds, the assembly of the trees and the burnout of refractory molds to cast the alloy. In addition, there is a significant environmental impact due to the combustion gases in wax burnout and the disposal of refractory materials.

The driving forces for Progold S.p.A. to experiment with the new SLM™ technology were several: to overcome the disadvantages mentioned in the previous paragraph; to improve the quality of metal alloys to avoid gas porosity, shrinkage and external inclusions; and to explore the possibilities of different geometries and materials used. This experimentation has opened up new scenarios to solve the typical problems of investment casting. Over the past few years, the effort by Progold S.p.A. in integrating selective laser melting in jewelry making has taken place through the selection of optimal printing parameters, the composition of precious and non-precious alloys, the types of supporting structures, and through comparative studies between the SLM performance as opposed to traditional investment casting in the production of critical elements of the jewel, i.e., items with reduced thickness, hollow objects, and decorative details such as pavé and ajour. These stages of the research journey have been shared over the past five years through purely technical-scientific articles, focusing on measurements and experimental results.

At this time, we have decided to pause and lift the observation point to look at the technological evolution with a more practical and operational eye, travelling through the experience gained over the years, facing several debates on the comparison between selective laser melting and traditional production techniques. Our journey in the last eight years has highlighted how the advent of SLM™ printing is to be considered one of the most important revolutions that the industry has experienced in recent decades. In this paper we want to give a practical response to a question that for many still remains unanswered: when and why is it worthwhile to directly print a precious or non-precious metal jewelry piece? The first study in this approach, presented in this article, compares direct metal 3D printing (SLM) with both traditional investment casting of wax patterns derived from carving, machining or a rubber mold—the 'queen' technique of the gold sector for versatility—and direct investment casting of printed pattern.

2. A COMPARISON BETWEEN TECHNIQUES

2.1 Melting and Modeling Mechanisms

The analysis meant to outline the strengths and weaknesses of investment casting in comparison with selective laser melting entails a clear and immediate understanding of the respective ways in which both ensure the melting phase of the material and the modeling into the desired shape. How would it be possible, in fact, to fully understand the added value of each technique without comprehending the key mechanisms of such processes?

In both traditional and direct investment casting, the melting process is simultaneous for all the material, which must fill the mold during the casting. Therefore, the alloy must be completely heated up to the optimal temperature, a process which is generally obtained in an industrial environment by means of special furnaces and crucibles. On the other hand, in SLM™ the temperature increase, needed to exceed the alloy's liquidus point, is provided by the interaction between the radiation of a thin laser beam and the material to melt, so that the melting in a given instant is very localized and only affects a restricted area around the point of the radiation beam. The solidification of the alloy is extremely rapid, as the laser keeps scanning, so that the amount of material involved in the melting process, instant by instant, is minimal. The objects build up through the addition of solid material, without macroscopic movement of molten metal masses.

Given the differences listed above, it seems clear how some characteristics of the material chosen for the creation of the jewel (i.e., jewelry piece) can be crucial in investment casting but not as relevant in case of selective laser melting or vice versa. In the case of investment casting, for example, either traditional or direct, the alloys' liquidus temperature plays a fundamental role in the feasibility and in the cost of the process. Indeed, high liquidus-temperature materials such as palladium, platinum and titanium alloys require casting machines whose components can withstand high temperatures and metal reactivity, as well as special coatings for the refractory molds. Moreover, the use of crucibles and ceramic molds could result in the contamination of the alloy to melt, a further source of defects in the final items in the form of inclusions and hard spots. In the case of titanium alloy casting, for example, the problem of contamination from the crucibles is so significant as to encourage the adoption of other—often more expensive—metallurgical techniques, such as the cold crucible arc melting, for the production of jewelry.[1] Nevertheless, some problems linked to the need to significantly raise the temperature of a consistent mass of material persist, such as thermal inhomogeneity of the molten mass, the heterogeneity due to segregation in the solid state, the vaporization of certain elements or their reaction with the residual oxygen.

On the contrary, in the case of laser melting, the temperature needed to melt the alloy is achieved through the interaction between the localized laser radiation and the material. The alloy absorbs the photons emitted by the laser source, whose energy is then almost instantly converted into heat. Therefore, the first key parameter to estimate the efficiency of the melting process is the ability of the material to be melted to absorb the particular wavelength of the laser. In the case of selective melting processes, the laser in use is typically in the near infrared, with wavelengths centered at 1064 nm (Nd: YAG) or 1070 nm (Yb fiber). The material's ability to absorb the radiation has to be evaluated in the infrared region.

The main obstacle to the laser melting of metals is their high reflectivity, for which the radiation is reflected by the surface of the material rather than being absorbed. This effect, directly related to the high electrical conductivity of the materials considered, is particularly emphasized in the case of gold, silver and copper. In fact, these elements have a reflectivity higher than 97% even at wavelengths nearer the visible spectrum. Other elements used in jewelry are less problematic from this point of view, as for example platinum or palladium which have, respectively, 74.5% and 80% reflectivity.[2]

A second discriminating parameter for the efficiency of the SLM™ process is represented by the thermal conductivity of the material. Once part of the radiation is absorbed, the sample acquires thermal energy that can be more or less quickly dissipated by conduction to adjacent areas. This implies a more localized heating for materials with a lower thermal conductivity coefficient, and a more diffused one in the case of alloys with higher thermal conductivity, in spite of the temperature reached by the area directly struck by the laser. With metals, it is generally known that thermal conductivity is proportional to electrical conductivity and temperature. Once again, elements such as gold, silver and copper are disadvantaged compared to other metals because of their high thermal conductivity (Table 1) which, together with their high reflectivity, leads to a higher laser energy required to melt their alloys as opposed to palladium-, platinum- or titanium-based alloys.

Table 1 Reflectivity and thermal conductivity values for some of the metals used in jewelry

Element	Reflectivity at 1070 nm (%)	Thermal Conductivity (W/mK)
Silver	98	429
Copper	97	401
Gold	97	318
Palladium	80	71.8
Platinum	74.5	71.6
Titanium	61.5	17

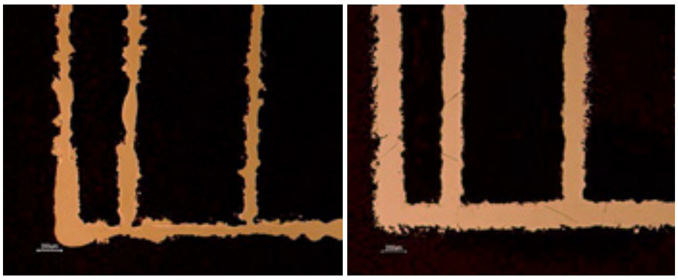


Figure 1 Single traces printed with 62.5 watt laser power and 0.33m/s scan speed: 750 red gold (left), 950 platinum (right)

One of the strategies implemented to increase laser absorption efficiency in the selective melting of gold alloys has been to add small amounts of semiconductor elements such as germanium or silicon, capable of lowering the electrical conductivity of the material.[3,4] A lower electrical conductivity in fact makes the alloy both less reflective and enhances localized absorption of laser energy. Nevertheless, despite the improved quality obtained with this compositional doping, the difference of efficiency in the selective melting of gold alloys compared to that of inherently more absorbent and less conductive metals remains high, even for metals that have significantly higher liquidus temperatures. A striking example is given by the traces produced by laser melting at identical parameters of a platinum 950 alloy and an 18K red-gold alloy with added germanium (Figure 1). In this case, the same amount of energy applied to the materials produces a very different result, namely thin and irregular traces in the case of red gold, a thicker and more consistent line in the case of platinum. Throughout the whole analysis, 750‰ gold and 950‰ platinum alloys were used as references.

With selective laser melting a reversal of the energy convenience of alloy melting, compared to investment casting, occurs such that printing platinum and titanium jewelry is more energy efficient than printing gold or silver objects. This is one of the great features that make this technique a real revolution. It is not trivial for any jewelry maker to have the opportunity to diversify their product range in the market, offering collections made of metals that are difficult to use with the traditional techniques. A specific reference is to 950 platinum and the difficulty to obtain complex, articulated jewelry pieces in this material (Figure 2). Among the non-precious metals it is worth mentioning titanium, particularly suitable for its intrinsic characteristics to selective laser melting. This material has recently attracted the interest of jewelry manufacturers for its properties such as hardness, biocompatibility and the possibility to color coat through anodization. Consequently, many new frontiers open up for all jewelry makers, always looking to offer innovative, cutting-edge products to the market. Designers find new inspiration and

Figure 2 Heart bracelet and ring, 950 platinum, printed by SLM™ (Designer: Xin Xin Zhou, IED Turin—Jewelry and Accessories Design Course)

Figure 3 Microstructure of a yellow gold item, obtained by SLM™ (left), traditional investment casting (center) and direct investment casting (right). In the case of SLM™, the measured average grain size is 30 micrometers; with investment casting, it is in the range of 90 micrometers.[5]

may feel freer to conceive shapes that until now were almost unfeasible.

More specifically, we shall better examine the differences caused by the selective and localized melting, which is typical of SLM™, and lost-wax casting. The extremely thin dimension of the metal layers made molten by the laser and the high solidification rate of the metal lead to a small average size of crystal grains, generally lower than that obtainable with investment casting of the same alloy (Figure 3), with the consequent improvement in mechanical strength.[5] Moreover, the inherently small grains of SLM alloys make it unnecessary to add grain refiners to the composition of the alloy, with the consequent elimination of some of the typical defects that may occur when using refiners, namely segregation and hard spots.

2.2 Geometric Limitations

2.2.1 Hollow Objects

In addition to the differences between investment casting and selective laser melting caused by the different metallurgical processes, the presence of the refractory mold in investment casting, with the related necessary operations for its production and metal filling, is a source of geometric limitations of the jewel, which can be overcome thanks to SLM™. An example is given of the impossibility of producing monolithic jewelry pieces with hollow insides almost isolated from the outside.

With traditional investment casting, the limitations on hollow objects arise already from the wax model production phase. With this technique the ways to obtain jewelry pieces with cavities, although always connected with the outer shell, and with controllable thickness, entail the use of a water-soluble wax core in the rubber mold, which is then dissolved prior to investing the flasks,[6,7] or the separate injection of the two halves of the hollow object and the subsequent joining of the waxes.

Making a hollow casing using a core requires the design of an appropriate opening in the wall of the object to support the core during wax injection and casting and allow core removal after both of those steps. In direct investment casting—although resin models can be created with cavities that are almost isolated from the outside, thanks to additive printing—the problem of producing hollow objects persists, since the liquid investment cannot penetrate into the internal cavities of the pattern except through a suitable number of openings. The investment slurry needs to be able to reach all the void areas inside the wax model to ensure a perfect reproduction. This implies, also for this production step, the necessity of a large number of openings to allow easy entrance of the refractory into the internal hollow part of the jewel. These openings are also needed to support the core inside the pattern and to allow the complete removal of the investment material after casting. A typical practical solution to bypass the limitations imposed by casting hollow jewelry pieces from combustible material models (wax, resin) consists in separately casting portions of the object to be later joined together. Joining by soldering, however, can cause additional problems, along with the occurrence of a further production stage. The problems generated in this case are related to the need to hide the joint line, whose color often does not correspond to the adjacent material, especially in the case of red gold, where the matching solder color disagrees with the need to have low melting temperatures. Additionally, the heating provoked by the joining operation causes tension to appear in the thermally affected zone, especially in the case of self-hardening alloys, which can lead to deformation and breakage of the pieces. Finally, the joining of thin-wall parts can lead to a real risk of accidentally melting wide areas of the items.

In selective laser melting these problems disappear, as the only requirement when printing hollow pieces is a limited number of tiny holes to allow the removal of the residual powder trapped within the object. As a consequence, we can obtain almost totally closed cavities without particular production problems, such as the bands in Figure 4 and the ring in Figure 5, where the displayed hollow can be filled or not filled with lattice structures to increase the mechanical strength. The ability to produce objects with closed cavities is a universally recognized strength of laser printing, as it allows reducing the final weight of the jewelry piece with the same overall dimensions, i.e., the same apparent volume. Practical applications of this possibility will be presented in Section 3.4.

Figure 4 Example of a hollow white-gold wedding band made by SLM™: 3D model (left) and printed object (right)

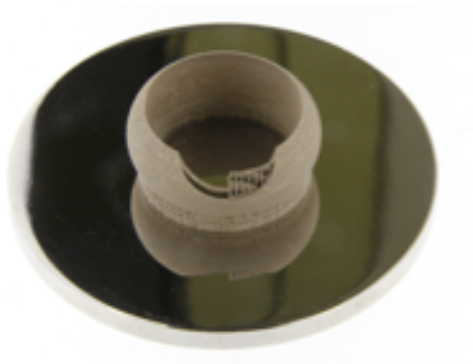


Figure 5 Hollow white-gold ring with and without supporting lattice structure

2.2.2 Thickness

The steps of creating the wax or resin model, producing investment molds and casting the molten alloy inside them also involve a second limitation of investment casting related to the jewel's design: the thicknesses of the pieces. The production of the model is problematic in the case of thin pieces since the injection of wax inside the rubber molds commonly becomes very difficult. The filling of thin walls often requires a condition of high compression of the wax, causing the rubber to swell and produce thicker or deformed models. The rubber molds can certainly be optimized to facilitate the filling, reducing the load loss and the wax cooling speed with a structure of the feeders, along with the use of waxes with better filling properties.[8] However, the presence of thin sections in a wax model always makes it considerably difficult to extract the model from the molds, with frequent and irreparable distortions and dimensional changes.

With direct investment casting, the use of additive manufacturing makes the phase of model production much less critical, although the clever choice of suitable polymeric materials, of the dewaxing cycle, of the printing technique and parameters, is critical to obtain an excellent casting quality without resin residues clogging the thin cavities to be filled.[9] Nonetheless, both investment casting techniques still entail the critical phase of pouring the metal into the refractory mold, which should ensure the complete filling of even the finer details of the jewel. The thinner and more extended is the hollow area is, the more difficult is the filling, due to the unavoidable and drastic heat exchange between the refractory and the molten alloy, whose surface tension may further hinder the metal flow.

The lower limit of the achievable thickness in investment casting, beyond any optimizations in the architecture of the models, is difficult to determine absolutely as it largely depends on the extension of the thin area and the overall geometry of the part. However, it is typically considered around 0.3–0.4 mm for filigrees and about 0.4–0.6 mm for the jewel walls with traditional investment casting, and 0.2–0.4 mm for the walls and 0.2–0.3 mm for filigrees with direct investment casting, always bearing in mind that the more extended the thin areas are, the more difficult their complete filling will be. Achieving and potentially exceeding these limit values—provided that the overall geometry of the piece makes it possible—still require considerable technical and technological effort through the use of complex feeding systems, and the increase of the metal overheating, of the gypsum mold temperature and of the gas overpressure in casting to improve the filling capacity of the material. These process adjustments, however, can cause adverse effects, such as the increase of gypsum reactivity with the molten alloy and a higher probability of refractory breakage at higher overpressures, resulting in the occurrence of refractory inclusions or form-filling defects. Moreover, the presence of the sections significantly increases the percentage of production scraps, since the number of incomplete pieces can drastically increase in a casting tree containing dozens of items. The success in the production of a single jewel cannot be translated in the success of series production.

Figure 6 Digital model (left), the section of the model with extended thin areas (center), and photograph of the printed titanium ring (right) with a 0.2 mm wall thickness.

Figure 7 Rings with extended lattice structure, with and without the inner wall, printed in red gold

With selective laser melting, thin sections and complex structures are not limiting factors since there is no wax model to make or filling of a refractory mold is involved in the process. The lower limit of the metal walls is given by the thickness of the single trace of laser melting, according to the minimum required robustness of the jewel. The minimum thickness of the melting trace clearly depends on the type of laser printer, the construction parameters and the type of metal powder. For the scope of this study with gold, platinum and titanium alloys, the minimum thickness is in the range of 0.1–0.2 mm. Moreover, thanks to the localized melting of the material, the overall geometry of the piece has little influence on thickness and minimum sections, which may possibly extend over the whole volume of the jewel.

This particular feature has allowed, in our production experience, to successfully print rings with extremely reduced wall thicknesses, down to 0.2 mm for extended areas of the raw jewel, as in the case of the printed titanium ring in Figure 6. It has also allowed us to print items with three-dimensional lattice structures, as in the mesh-like ring in Figure 7, which represents the natural extension of the filigree two-dimensional structure without the limitations imposed by the mold-filling process.

It is worth thinking about how designing for and manufacturing with SLM can be an additional and important revolutionary element. Not only is it a new way of conceiving and designing the shapes, but SLM also optimizes the investment of precious metal in the object. The jewel inherently represents an element of recognition within consumer society, which places an emphasis on the aesthetics aspect as well. Playing with the thickness allows for determining in advance how much material to use for the jewel and gives the opportunity to wear a bulky accessory of strong aesthetic impact, dramatizing the shape without paying for the high specific weight of the precious material. We will later discuss this topic later in more detail.

2.3 Definition and Dimensional Consistency

The thickness of the single printed trace in selective laser melting, in addition to representing the minimum achievable wall thickness, is more generally the resolution limit of this technique on the platform plane (X–Y). Just as it happens in the artistic design of a jewel, it is impossible to create details with smaller dimensions than the pencil trace to draw them. This entails a poorer definition on the construction plane (X–Y) with selective melting

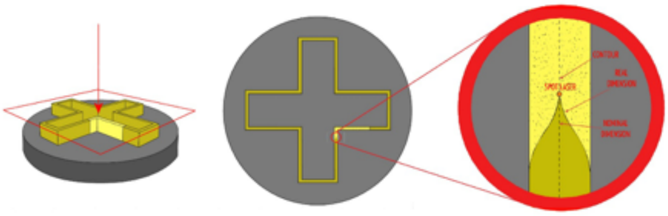


Figure 8 Intrinsic thickness of the melting trace and effects on the real dimensions of the pieces

compared to the one obtainable through traditional investment casting, if the projection of the decorative details is limited to a few tenths of a millimeter. Besides these projection values, with investment casting the form filling problems discussed in Section 2.2.2 intervene, for which the values of minimum thickness, and therefore of reproducible details, unavoidably increase leading in fact to a worse resolution. [I'm sorry but I have no idea what those two sentences say.] On the contrary, with selective laser melting, the minimum achievable thickness depends only on the width of the melting trace regardless of the extension of the thin area. Therefore, the maximum achievable definition on the construction plane X–Y remains constant irrespective of the geometry of the part to print.

As for direct investment casting, the resolution depends on the system used for the resin or wax model production but in general, especially in the case of resin printers, the resolution comes to be even greater than the one obtainable in traditional casting, always considering details with projections of a few tenths of a millimeter.

Note that the resolution in selective melting is much higher when considering the z-plane. Indeed, in this case the resolution depends on the height of the single printing layer, which, in SLM™, can reach values of 20 micrometers, 10 times lower than the trace width in the X–Y plane. Due to the thickness of the melting trace, in SLM™ a compensation by the printing software is necessary for compliance with the nominal dimensions of the pieces, stopping the construction before the geometric edges of the piece (Figure 8). In other words, the outermost laser scanning corresponding to the outline of the object is never carried out, otherwise the final dimensions of the piece would be greater than the desired ones. In fact, it is performed more internally, within the distance of half the melting trace so as to compensate for the intrinsic thickness.

The dimensional non-compliance of the pieces is mainly caused by the shrinkage of the material as the temperature decreases both in investment casting and selective melting. This happens, however, in different modes depending on the chosen technique. In investment casting, solidification takes place simultaneously on the whole piece and implies a certain dimensional variability depending on the position of the pieces on the casting tree, for example, since the position of the thermal center may change significantly. On the other hand, the mechanical stress caused by the shrinkage is partially eliminated while the alloy remains inside the high-temperature molds.

In selective laser melting, solidification takes place by layers, thus leading to a preferential direction in the development of the residual tensile stress. The low production temperatures do not allow the elimination of residual stress, which can deform, flake or tear the pieces from the platform. One way to limit the effect of these stresses is to appropriately plan the position of the object on the build platform. On the other hand, the independent growth of each piece and its progressive construction guarantee a high dimensional consistency of the pieces.

2.4 Supports and Feeders

In addition to the examples above, a complete comparison of the advantages and disadvantages of selective laser melting compared to investment casting must take into account the presence of supports in the former and feeders in the latter. These elements are indispensable to secure the growth position of the jewels in one case, and to allow the flow of the molten alloy inside the molds in the other.
In laser printing, the presence of supports is also needed for heat dissipation and to hold up the undercuts parts of the object, which otherwise could be easily swept away by the movement of the screed used for metal powder distribution. The shape and position of the supports are chosen as to make the removal of the pieces from the platform easier and cheaper. They mainly appear as three-dimensional lattice structures, with very thin contact points to the piece. Just like the feeders in investment casting, the printing supports are also precious parts to be removed from the jewel; therefore, their quantity is a factor to be considered in the general economy of the manufacturing process as they represent production scraps. Compared to the feeders in the casting trees, the structure of the printing supports generally constitutes a less important portion of the precious metal employed in the production process, so that the working loss in laser printing is usually lower than in investment casting. Nevertheless, it is worth noting that particular geometries of the jewelry pieces may require special supporting, which could lead to a disadvantageous ratio between the volume of pieces and volume of the supports.

Supports are also generally required in direct investment casting for the printing of wax or resin models, but in this case they are removed before production of the investment molds and the assembly of the tree. They affect the production process only in terms of time required for their removal, but not in terms of the quality of the cast pieces or of the scraps.

An important difference between supports and feeders is their dependence on the volume of the jewel to produce. In investment casting, bulky items require enormous feeders to move the thermal center outside their volume in order to avoid shrinkage porosity, for which there is a limitation in the maximum achievable thickness of the objects, given the typical dimensions of the molds. The steel flasks for lost-wax casting generally hold a maximum of less than two kilograms of refractory material, with a diameter of the cylinders within 10–15 cm and a height of 10–30 cm, so that the maximum achievable thickness of the pieces is around 5–10 mm on average. Moreover, in these cases the feeder can represent a high portion of the total mass, which means high scrap production and limited number of jewels for each flask, thus resulting in a great lowering of productivity with consequent raising of the costs. In selective laser melting, the size and number of the supports is only affected by the surface extension of the objects. In this case, scrap production from the supports does not increase along with the mass of the item, as it depends on the overall surface of the workpiece rather than on its volume.

The main drawback of the supports in selective melting concerns their removal. In fact, some residual parts may remain attached to the printed jewel or there could be craters due to the tearing of some material attached to the end of the supports. The extent of

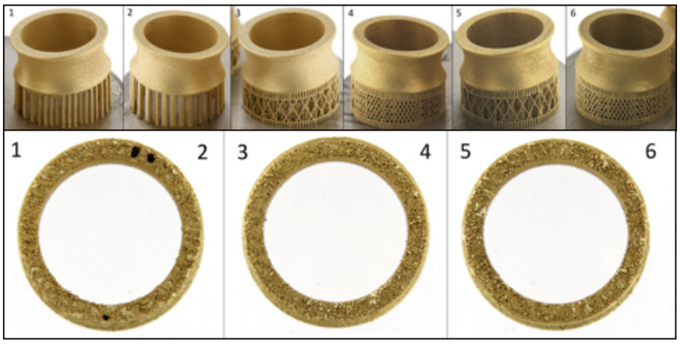


Figure 9 Hollow rings printed with different supporting systems and the lower surface of the samples after supports were manually removed. Holes caused by the removal of columnar supports are clearly visible in samples 1 and 2.

Figure 10 Example of support breakage in a white-gold jewel

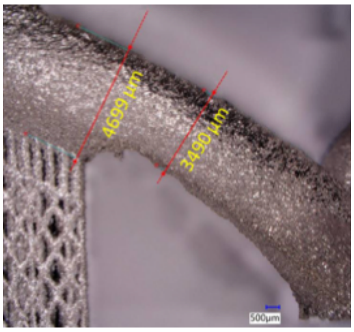


Figure 11 Titanium ring printed with insufficient supporting

Figure 12 Example of a ring, not suitable for 3D printing

Figure 13 Ring with a geometry suitable for selective laser melting, given the minimal need of supporting for its production

these defects and the capability to eliminate them in the finishing phase depend on the type of supports: the more massive they are, the more difficult it will be to remove them, also leading to the increase of the production process loss (Figure 9).

Choosing the most suitable support system for each jewel entails a compromise between the least invasive impact and best possible features in terms of structural support and thermal dissipation. Indeed, just like an inadequate feeding system can lead to shrinkage, form filling and breakage problems in investment casting, unsuitable supports can be a source of other production problems in selective melting. For example, in the case of supports that are too widely spaced or too thin, phenomena such as collapse, displacement and overheating of the piece may occur so that the final quality of the jewel is compromised. In the case of excessive supporting, the roughness of the connecting surfaces can be very high and detachment is difficult.

Each material has a critical angle to the horizontal over which supporting is not necessary to print the objects, since the inclination of some surfaces is high enough to be self-supporting, thus saving time and material. For this reason, the operator's skills can play a crucial role in achieving the best possible quality by adjusting the orientation of the object on the printing platform to minimize the areas affected by the supports. Some of the issues related to inadequate supporting are illustrated in the following examples. Figure 10 shows an example of too weak supports resulting in their breakage and incompleteness of the printed object. When the supported area is insufficient, usually there is a lack of material in the unsupported parts, resulting in a spongy-looking surfaces or actual cavities. Figure 11 is an example of a titanium jewel with insufficient support, pointing out the area lacking material, whose nominal diameter should in fact be identical to that of the supported area.

The necessary presence of a certain amount of supports obviously affects the design of the printable objects. In the case of fine decorative details or gem setting, as in the example shown in Figure 12, the residue left by the supports is often incompatible with the level of definition required by the piece, resulting in an unsatisfactory printed jewel in terms of quality.

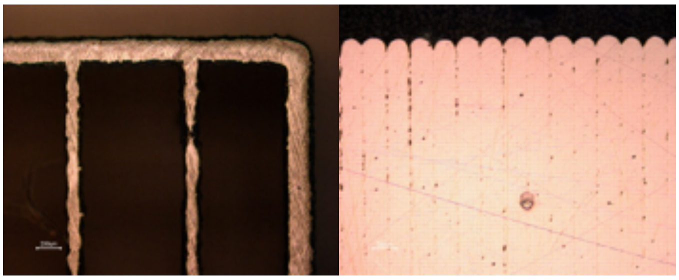
The most suitable jewels for selective laser melting are the ones in which, by their geometry, all surfaces have an inclination higher than the critical angle for the employed material, so as to require only minimal supporting. An example of a ring corresponding to this criterion is presented in Figure 13, in which the supports are necessary only in the lower tips of the jewel to fix it on the build platform.

2.5 Defects

Beyond the differences imposed by the materials and the design of the jewels, the diverse physical principle related to the production of the objects is the source of another important difference between the two techniques, concerning the type of microstructural defects created in metal alloys. The general analysis of defects occurring in an object obtained by investment casting reveals that they are caused mainly by the chemical and physical processes that take place during the production stages, while, in the case of laser printing, the defects are mainly of a physical type, since there is no interaction between the wax, the mold, the crucibles and the molten alloy. This is the main cause of their great diversity in terms of their nature, shape and localization within the jewel.

The main types of microscopic defects typical of both traditional and direct investment casting are shrinkage and gas porosity, hard spots due to refractory inclusions and grain refiners, intermetallic compounds, inclusions from graphite crucibles, and carbonaceous residues of waxes.

Shrinkage porosity is due to the volumetric change occurring after the material solidifies, since the density of the alloy in the liquid state is significantly different from that in the solid state. When, after the solidification, additional liquid metal cannot reach and fill the cavities left by the volume change, these will remain visible as dendritic porosity. The occurrence of this complex casting defect is thus linked to both the actual volume changes, and the cooling rate of the alloy in the mold, with regard to the possibility for the still liquid metal to reach and feed the critical zones. The shrinkage of the metal alloys or, more rarely, their expansion is an unavoidable intrinsic process in the state change from liquid to solid, which can be limited thanks to a more suitable alloy composition, or concentrated mainly in the sprue through a well-thought-out choice of position of the feeders. Thanks to the different construction mechanism of selective laser melting, i.e., not simultaneous but in consecutive layers, these types of defect are generally not present.



(a) (B)

Figure 14 Trace with incomplete laser melting (a), porosity due to incomplete melting of adjacent traces (b)

In the case of selective laser melting, it is possible to find porosity from lack of material due to incomplete melting, which can be caused by a partial melting of the powder in the single laser trace (Figure 14a) or by the incorrect distance between adjacent traces (Figure 14b).

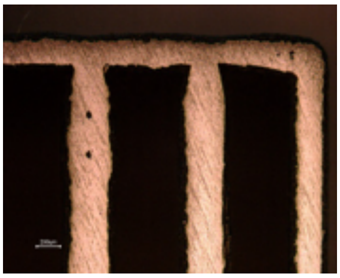


Figure 15 Gas porosity in the single printed traces

Instead, gas porosity can occur both on items obtained by investment casting as well as on pieces printed by selective laser melting but with different origins. With investment casting, gas porosity is mainly caused by the decomposition of the gypsum in contact with the molten alloy at a high temperature, and in this case it is mainly located on the more superficial areas of the pieces, close to the interface between gypsum and metal. It can also be caused by the evaporation of the alloy components. In the case of selective laser melting, gas porosity is generally caused by trapped argon during the turbulent melting process or by the momentary and partial vaporization of the metals with high vapor pressure during printing.10 This porosity generally has no specific distribution but can occur throughout the whole piece. An example of gas porosity an SLM piece is shown in Figure 15, with distinctly noticeable spherical cavities in the center of the traces produced by individual laser scans.

The defects related to the presence of extraneous materials, incoherent with the metal matrix, represent another broad family of imperfections to be found in jewelry making. In lost-wax investment casting, the refractory inclusions due to the abrasion of the molds and the graphite inclusions caused by the degradation of the crucibles are very frequent and damaging. These defects result from the traditional use of molds and crucibles; therefore, they are totally absent in selective laser melting. Other types of extraneous inclusions typical of casting are caused by hard spots of intermetallic compounds or grain refiners, which are expelled from the matrix due to compositional imperfections or incorrect cooling processes. In laser printing the latter type of inclusions is quite rare, both because the cooling speed is extremely rapid, enough so as to avoid the growth of crystalline nuclei, and also because grain refiners are typically absent.

Concerning inclusions due to contamination, these can potentially occur both in investment casting and in selective laser melting. In the case of casting, in addition to an improper reuse of scraps, contamination can be caused when the same crucibles are used to cast alloys with different compositions. Such a problem can be completely avoided by using different crucibles for alloys with different compositions. In selective laser melting, this possibility is much more problematic to manage. If a laser printer is not properly cleaned before changing the alloy in the machine, it is likely to get contamination from the previously loaded powder, with consequences such as fragility of the pieces up to the non-compliance of the gold fineness. Changing the working material is much more problematic in selective laser melting compared to investment casting, due to the difficult process to clean the printer. In jewelry making, the pieces often printed in different alloys but limited in number and with a fixed composition. This problem can be overcome by using different printing machines, each one dedicated to a particular precious alloy.

In addition to the defects listed so far, there are other possible problems typical only of investment casting due to the extra steps in the production process, i.e., the creation of a wax or resin model for the subsequent production of the mold. Among these problems are incomplete filling, bubbles and irregular surfaces on the wax model, or residues caused by an improper dewaxing process, especially in the case of the resins.

With regard to macroscopic defects, in investment casting there can be concentrations of solidification shrinkage with the formation of visible sinks in sections of the pieces. Cracks can also form due to segregation of low-melting or fragile phases on the grain boundary, as well as lack of material due to incomplete filling of the molds. With selective laser melting, collapses and lack of material due to inadequate supporting can occur, as well as cracks and deformations due to the internal residual stress of the pieces. The latter are due to the printing mechanism in SLM™, in which the workpiece builds up in consecutive layers, accumulating mechanical stress due to material shrinkage after cooling. In general, these stresses, which can be reduced thanks to an annealing heat treatment, can cause breakage of the supports (as seen in Figure 10), delamination or deformation of the pieces. The latter can occur both in terms of dimensional change with respect to design and with the bending of the object once the supports are removed.

3. A COMPARISON OF PERFORMANCE
3.1 Versatility

During recent developments in jewelry production by laser printing, this technique has shown the amazing ability to overcome some of the inherent obstacles of the precious materials used in lost-wax casting. In the latter case the limitations imposed by the melting temperature and the reactivity of materials restrict the number of structural elements to potentially use in precious alloys to about a dozen metals, plus a few other additive elements for the adjustment of the microstructure, such as grain refining, and age hardening, and for deoxidation. This limitation greatly

Figure 16 18K white-gold wedding bands with 16% Ti and 19% Nb

restricts the level of mechanical and optical performance that a precious metal casting alloy can achieve, whereas the advent of selective laser melting has allowed, at least in part, to realize new characteristics thanks to the possibility to alloy elements, that are extremely reactive and refractory, not possible in traditional casting.[11] An example is the use of niobium and titanium to almost prohibitive levels for investment casting (19% and 16%, Figure 16), using selective laser melting of metal powder mixtures, thus reaching a premium white yellow index. Moreover, thanks to titanium low density, it was possible to obtain 18 K gold alloys of exceptional lightness (12.0 g/cm^3), approximately 25% less than a white palladium alloy. A drawback of these innovative alloys currently involves the test of their gold fineness, since many refractory metals significantly interfere with the fire assay.

3.2 Quality: Density and Roughness

In recent years, the R&D laboratory of Progold S.p.A. carried out several studies, with the aim of comparing the quality of jewelry pieces produced with selective laser melting and with traditional and direct investment casting.[5,12,13] According to the results, it appears that the fundamental characteristics for assessing the quality of the jewels are density and surface roughness; such parameters are also directly related to the robustness and the definition of the jewels.

The density of the pieces is actually a direct or indirect measurement of residual porosity, a defect causing considerable difficulties in obtaining jewelry with aesthetically pleasing surfaces. Instead of the most common indirect method of Archimedes for the porosity measurement—only sensitive to the inner porosity of the material—we have generally preferred a direct measurement in our studies by digitally analyzing the images of sample sections, obtained with optical or electron microscope, in order to evaluate the area affected by the porosity in relation to the total observed area.

The results obtained from the comparison of the residual porosity between items produced by laser printing and traditional or direct investment casting have generally always highlighted a greater final density of the SLM™ piece, for the same alloy composition.[5,12] With the same simple ternary alloy (Au-Ag-Cu), the porosity of a product made by laser printing is about twenty-five times lower than that achieved by traditional or direct investment casting (Table 2). An important deviation from this trend can be observed in the case of the same alloy modified with gallium, which has indeed improved the characteristics obtained in traditional and direct investment casting, but has significantly worsened the quality of the alloy produced by selective laser melting, mainly because of the intense particle projection during its construction, detrimental to an ordered construction of the piece. This is why in this case, the measured residual porosity is lower with investment casting (0.05%) than with laser printing, although the measured value remains still higher than that obtained in selective laser melting with a gallium-free alloy (0.01%).

Table 2 Residual porosity in 18K gold alloys with traditional, direct investment casting and SLM™[12]

Production Method	Porosity Au-Ag-Cu Alloy (%)	Porosity Au-Ag-Cu-Ga Alloy (%)
Traditional Casting	0.25	0.05
Direct Casting	0.25	0.05
SLM™	0.01	0.47

In a similar manner to density, the roughness has also been the subject of extensive studies over the years, involving different alloys and objects with surfaces at different inclinations. In our studies we have chosen to consider the parameter of total roughness (R_t) of the profile, corresponding to the difference between the highest point and the lowest point of the surface, acting as a reference value for the comparison between the techniques. In fact, this parameter represents the precious material thickness which must be removed in the polishing phase in order to obtain a perfectly smooth and aesthetically satisfactory surface.
The results of the various analyses carried out have always shown a greater roughness in the objects produced by laser printing, due to the inherent growth method of the technique. The roughness decreases going from objects produced by direct casting to traditional investment casting. It should be noted, however, that in the case of direct casting, the final roughness depends on the type of prototyping machine used. In the present study, a multi-jet wax printer was preferred with respect to resin printers for the lower carbonaceous residue after de-waxing even though the printed objects had a higher final roughness than those produced by the best stereolithography printers. The results obtained for an 18K yellow-gold alloy, with measured roughness of surfaces at different angles to the horizontal plane, are summarized in Table 3.

Table 3 Minimum, maximum and average roughness of 18K yellow-gold samples from traditional, direct investment casting and SLM™[12]

Production Method	Rt min (µm)	Rt max (µm)	Rt average (µm)
Traditional Casting	10.8	39.9	22.0
Direct Casting	18.6	44.9	27.3
SLM™	22.1	59.1	31.3

3.3 Mechanical Characteristics

The mechanical characteristics, typically measured by means of tensile and hardness tests, affect some distinctive features for jewelry production and finishing processes, as well as the final performance of the items. In general, high elongation and strength at failure translate to good material plasticity and allow for easier gemstone setting and repairing, for instance, replacing a chipped stone. A good hardness means a higher resistance to wear and scratch, together with stronger and more secure stone settings.
In our previous research works we presented a comparison between the mechanical properties of items produced with SLM™ and traditional lost-wax investment casting of yellow gold[5], red gold and platinum.[13] In Table 4 we present the results for 18K palladium white-gold alloys as produced, without further

thermal treatments. The specimens used for this comparison have similar chemical composition with the same palladium content, but are optimized for the specific production pathway. For example, in the case of investment casting the alloy contains a grain refiner. Both alloys are available on the market and are actually used for jewelry production in white karat golds.

Table 4 Mechanical characteristics of palladium white golds (18K) from investment casting and SLM™, as produced

Production Method	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation at Failure (%)	Hardness (HV)
SLM™	344 ± 28	460 ± 39	21 ± 8	154 ± 2
Investment casting	283 ± 14	480 ± 25	33 ± 9	174 ± 5

The comparison between the tested items indicates a slightly lower hardness for the SLM™ items, while the values for ultimate tensile strength are similar. The elongation at failure is higher (33%) for items produced with investment casting, a trend already observed in the past for yellow and red gold and for platinum. These values imply a more malleable material obtained with investment casting, leading to a possible lower failure risk, for example, during stone setting.

Figure 17 Digital model of the ring used for the finishing loss calculation

3.4 Finishing Loss

The finishing loss is mainly related to the total surface roughness of the pieces which, in fact, represents the minimum thickness of material to be removed to obtain a compact and bright surface. In the case of investment casting, the maximum roughness was around 40 and 45 micrometers, respectively, for traditional and direct casting. With SLM™-produced parts, which have a higher roughness value, the layer to be removed during polishing is thicker.
A comparison between the finishing loss in identical objects produced by both processes is actually not very fair, since selective laser melting is usually preferred for objects that normally cannot be cast. However, just to give an idea, a theoretical calculation of the precious metal loss during finishing is presented in Table 5, by considering the red gold wedding band in Figure 17 with a density of 14.84 g/cm^3.

Table 5 Polishing loss calculated for a ring produced by investment casting and SLM™, by volume and weight

Production Method	Thickness of Polishing Loss (mm)	Relative Volume (cm^3)	Loss (g)
Traditional Casting	0.040	0.055	0.8
Direct Casting	0.045	0.062	0.9
SLM™	0.060	0.082	1.2

Note that the estimate of volume lost does not account for void areas in the valleys between the peaks on the rough surface removed.

The data reveal that, in both traditional and direct investment casting, the loss is lower than in selective melting. In the latter, the impact of the supports should also be taken into consideration, although it may vary depending on the size of the supported surfaces. As explained earlier, the surfaces affected by the supports may present surface defects in the form of excessive or lacking material, so that deeper polishing is often necessary in such areas. In the case of investment casting, the occurrence of porosity under the superficial layer, which is more likely than in Selective Laser Melting, can result in the need for additional polishing in order to achieve the required quality in high-class jewelry, with consequent loss of a greater amount of precious metal.

3.5 Thickness, Volumes and Weight Control in Selective Laser Melting

As explained in the previous sections, one of the added values of the selective laser melting technique compared to investment casting is represented by the possibility of producing hollow objects with thin walls and lattice structure. A brief summary of the geometric limits for the three subject production techniques is presented in Table 6.

Figure 18 Digital model of the ring used for calculations in Table 6 and Table 7

Table 6 Summary of the geometric limits in investment casting and SLM™

Production Method	Wall Thickness Limit (mm)	Filigree Thickness Limit (mm)	Hollow Objects
Traditional Casting	0.4–0.6	0.3–0.4	No
Direct Casting	0.2–0.4	0.2–0.3	No
SLM™	0.1–0.2	0.1–0.2	Yes

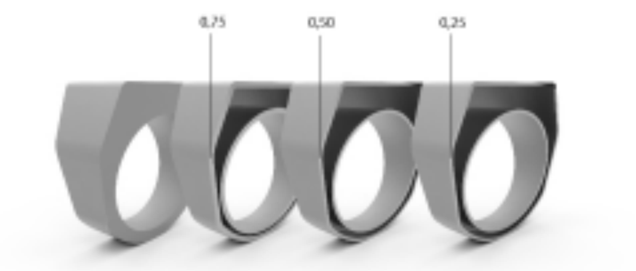


Figure 19 Digital model of the platinum ring at various levels of hollowness

Thanks to SLM™, it is possible to conceive jewelry pieces that, at equal apparent volume, are in fact much lighter than those obtainable with traditional or direct investment casting since the interior can be hollowed out, with the consequent saving of precious metal. Moreover, thanks to the possibility of creating three-dimensional lattices, supporting structures can be inserted into the cavities to increase the mechanical strength of the pieces with minimal impact on the weight. An example of weight reduction achievable by producing hollow objects is presented in Table 7 for the ring in Figure 18.

The weight variation of a platinum ring is calculated in Table 7, going from a solid ring (as obtainable by traditional or direct casting) to SLM rings with progressively thinner walls without the addition of supporting lattices (Figure 19).

Table 7 Weight variation depending on the wall thickness for platinum rings

Alloy	Wall Thickness (mm)	Weight (g)	Weight Reduction (%)
Pt	2.5	33.2	0.00
	0.75	17.7	46.5
	0.5	12.5	62.3
	0.25	6.6	80.2

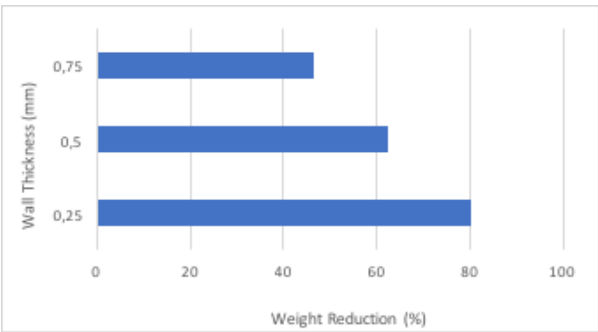


Figure 20 Weight reduction as the pieces are progressively hollowed out in SLM™

As shown by the data, for platinum it is possible to obtain a weight reduction of almost 50% with a 0.75 mm wall, up to a savings in weight of more than 80% with 0.25 mm walls. Moreover, by hollowing out the pieces, hollow objects represent a way to create wearable jewelry with high volume, which otherwise would be too heavy if they were solid. In investment casting, as previously explained, the only way to obtain a jewel with a completely closed cavity is to produce the two halves separately and then weld them together. Examples of hollow rings with large volume printed by SLM, no welding needed, are shown in Figure 21.

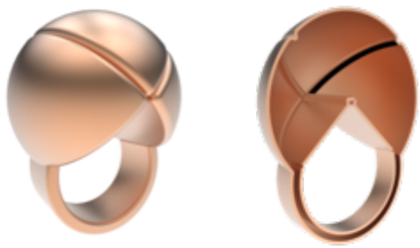


Figure 21 Model of highly voluminous ring

Besides the reduction of weight to increase the wearability, a partial hollowing out of the rings allows to obtain the same final weight in different sizes of the same model. This is an advantage when the price to the public is fixed for a given ring model (standard practice for high end Jewellery), and not calculated on a weight basis, as happens in mass products. When producing the piece by investment casting, either the amount of precious metal increases along with the ring size, or the item's thickness decreases, which changes the external appearance of the ring. Instead, with SLM™, it is possible to insert internal cavities for larger ring sizes that compensate for the total additional volume, thus obtaining objects with constant weight and volume within the whole range of available sizes.
Table 8 shows the calculated final weight for the ring in Figure 18, in the case of a yellow gold alloy, at different sizes without internal cavities, like in investment casting, and with cavities conceived to obtain a constant weight upon all the available ring sizes (Figure 22).

Figure 22. Different sizes of the same yellow gold ring ring with identical final weight.

Table 8 Weight variations of the yellow-gold ring as size increases compared to no weight variations in rings with enlarging inner cavities as size increases

European Size	Solid Ring Volume (mm^3)	Solid Ring Weight (g)	SLM Ring Volume (mm^3)	SLM Ring Weight (g)
48	1454	22.2	1454	22.2
50	1527	23.3	1454	22.2
52	1603	24.4	1454	22.2
54	1680	25.6	1454	22.2
56	1757	26.8	1454	22.2
58	1837	28.0	1454	22.2
60	1919	29.3	1454	22.2

3.6 Production Lead time

The time required to deliver an order obviously depends on the number and type of pieces to produce. Nevertheless, from the comparison between different production techniques, not only the lead time for a given number of items is different, but also the calculated production time significantly changes for the various techniques when considering batches of different quantities. The comparison between selective laser melting, traditional and direct investment casting, was done for the production of one, ten and one hundred reference gold rings.

The pieces used for the lead-time comparison are of the same alloy, have an identical volume and, therefore, mass of around ten grams, while the considered shape changes depending on the chosen technique. The designs were chosen according to the typical geometry generally produced with each of the techniques in analysis, specifically, a band ring for traditional and direct investment casting and a hollow ring for selective laser melting. In this way, the simulation of the lead time is performed on jewelry pieces that, for their design, would be actually produced with one technique rather than another among those under consideration.

The calculation of lead time takes into account the typical production time of high-end gold jewelry, for which selective laser melting is particularly suitable because of its innovative potential. The analysis of the production capacity presented in the next section is also performed considering this industry.

The time needed for the study and design of the model was not taken into account in the calculation, as it represents a phase belonging to all three techniques under consideration. The availability of the production machines has been considered as the same for each type; therefore, the calculation of production time and process productivity was carried out admitting only one item of equipment for each production stage, i.e., one wax injector, wax jet printer, machine for investing, a burnout furnace, casting machine, laser printer, and so on. The production capacity for each device corresponds to the average in the gold market, so in the calculation of the differences between the various techniques, exceptional performance machines are excluded

For each technique, we have calculated the time required to complete each production steps, as summarized in Tables 9-12 and in Figures 23 and 24. The phase of prototype production in traditional investment casting includes the creation of the wax model using a 3D printer, its casting in non-precious metal and the finishing phase.

Finally, wax preparation time can be further reduced if a second rubber mold is employed to be used during the cooling time of the wax in the first mold. However, in this case, even for the production of one hundred pieces, the time saved in the preparation of the wax is more than consumed by the preparation of a second rubber mold, which was therefore excluded from the calculation of production time. The printing time for direct investment casting was estimated based on the use of a multi-jet printer ProJet® CPX 3500 plus (3D Systems).

Table 9 Estimated production time of traditional investment casting

Traditional Investment Casting			
Production Phase	Working Time 1 piece (min)	Working Time 10 pieces (min)	Working Time 100 pieces (min)
Prototype Creation	1150	1150	1150
Preparation of Rubber Mold	120	120	120
Injection of Waxes	1	10	100
Assembly of the Tree	1	3	33
Preparation of the Flask	30	30	45
Flask Burnout	720	720	720
Alloy Pre-Melting	15	15	15
Melting and Casting	15	15	60
Pickling	5	5	20
Cutting of Sprues	0.25	1	10
TOTAL (approximate)	**2050 (34.0 h)**	**2070 (34.5 h)**	**2270 (37.5 h)**

Table 10 Estimated production time of direct investment casting

Direct Investment Casting			
Production Phase	Working Time 1 piece (min)	Working Time 10 pieces (min)	Working Time 100 pieces (min)
Printing of Waxes	260	270	710
Removal of Wax Supports	60	60	90
Assembly of the Tree	1	3	33
Preparation of Flask	30	30	45
Flask Burnout	720	720	720
Alloy Pre-Melting	15	15	15
Melting and Casting	15	15	60
Pickling	5	5	20
Cutting of Sprues	0.25	1	10
TOTAL (approximate)	**1100 (18.5 h)**	**1120 (18.5 h)**	**1700 (28.5h)**

Table 11 Estimated production time of selective laser melting

Selective Laser Melting			
Production Phase	Working Time 1 piece (min)	Working Time 10 pieces (min)	Working Time 100 pieces (min)
Supporting of Digital Model	15	15	15
Printing & Cleaning of Machine	110	440	4400
Removal of Supports	3	30	300
TOTAL (approximate)	**130 (2.0 h)**	**480 (8.0 h)**	**4700 (78.5 h)**

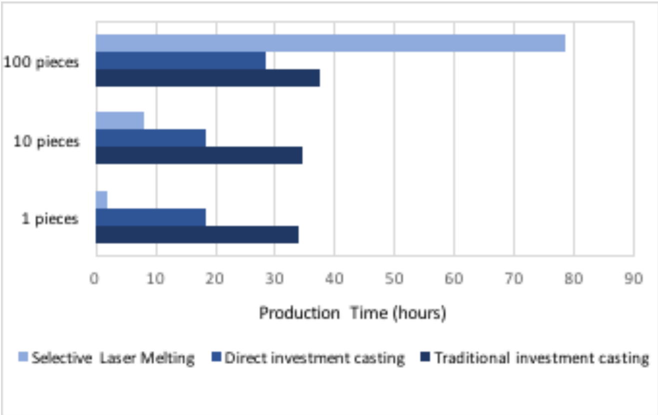


Figure 23 Production lead time of the three techniques depending on the number of pieces

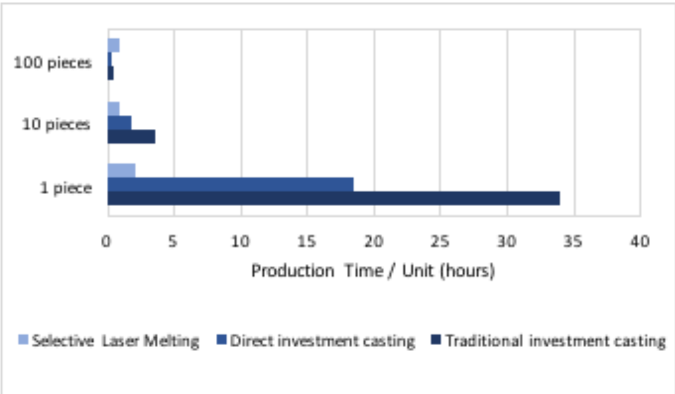


Figure 24 Production time for the single unit depending on the technique and the number of pieces

Table 12 Summary of the estimated production times for the three tecniques

Production Technique	1 piece (hours)	10 pieces (hours)	100 pieces (hours)
Traditional Casting	34.0	34.5	37.5
Direct Casting	18.5	18.5	28.5
SLM™	2.0	8.0	78.5

Lost-wax casting has become, the leading technique in jewelry manufacturing in recent decades, thanks to its production flexibility. However, when comparing the production time between traditional, direct investment casting and laser printing, it is immediately evident that for limited productions in the range of a dozen units, the lead time with selective melting is much lower than with the other techniques. For a few pieces, traditional investment casting requires the longest time, because of the considerable impact of prototype production on the overall number of working hours. This is why the production of a single piece with traditional investment casting is actually a very rare event, only justifiable for jewels of great artistic importance, so that direct casting is generally chosen in this case. When an old serial production is resumed, for which prototypes and rubber molds are already available, the time for the creation of one or ten pieces in traditional investment casting is considerably reduced, in fact shorter than in direct casting, but still longer than in selective laser melting, due to the long time needed for the preparation and firing of the investment molds. The situation is the opposite with a higher number of pieces, close to a hundred. In this case, the laser printing time becomes longer than the time needed for the creation of the prototype, the burnout cycle of the investment molds and printing the waxes, thus making investment casting an overall faster production process compared to selective laser melting.

For the production of one hundred pieces the lead time of traditional investment casting rates are is still longer than that of the direct investment casting, due to the long preparation time of the prototype. With a higher number of produced parts the lead-time trend is reversed, i.e., prototype production time for traditional investment casting is amortized while the wax pattern printing process, longer than the wax injection step, limits direct investment casting. For example, in the case of producing 225 items equal to nine complete flasks, the lead time is 43.5 hours for traditional investment casting and 45 hours for direct investment casting, a difference in lead time that further grows by increasing the number of pieces to simulate the production of a large series of jewels.

The advantage in production rate for a relatively small number of units can be very useful in a world in which the desire for originality and customization has become a cornerstone for each company, such as in the automotive, clothing and watchmaking industries. This mass phenomenon inevitably also affects the industry of goldsmith manufacturing and fine jewelry. In the past, goldsmiths from time to time used to manufacture unique jewelry pieces for a single customer, whereas nowadays, thanks to laser printing, it is possible to consistently offer a faster service. In fact, selective laser melting, unlike investment casting, allows the creation of a unique jewelry piece directly in precious metal without the whole production cycle of casting. Moreover, thanks to its ability to produce very light pieces maintaining or even increasing their overall volume, selective laser melting enables the creation of voluminous, showy jewelry, which at the same time is light and wearable.

When mass producing a single jewel, the advantages of investment casting are still evident compared to selective melting. Here, the choice of the selective laser melting technique can be justified only in the case of critical geometries of the pieces (i.e., thin walls, extended lattices, hollowness), with materials that are problematic in casting such as platinum and titanium, or in the case of particular economic advantages such as weight reduction of hollow objects or the possibility of keeping the weight constant for rings and bracelets in different sizes.

In order to meet the designer's needs, it is now possible to receive a sample of the actual series production in just a few hours. Such a revolutionary speed in construction has a considerable impact on the entire supply chain of the jewel with the aim to supply the retail stores with limited series of jewelry in a short time.
For limited collections, unique pieces and niche markets, selective laser melting overturns any traditional lead-time cycle, significantly shortening the more time-intensive production phase.

3.7 Production Capacity

One of the most important aspects for a proper benchmark is production capacity. Production capacity is the quantity of jewels produced every day and it has been defined as the mass of the pieces produced on a daily basis, as determined by traditional industrial standards. Our analysis is based on using one of each of the necessary machines with average production capacity for each one during one eight-hour shift, five days a week. Also, a single operator for each production department was considered so, for example, in the case of traditional investment casting, the wax operator will be able to prepare waxes, build and invest trees while the caster will simultaneously start burning the flasks, cast and cut the sprues. In the case of operations involving automatic machinery, we considered that it could operate until the end of the production cycle also outside regular working hours.

In the case of traditional investment casting, a single furnace normally can complete just one burnout cycle during the working day due to the long duration of the dewaxing process of the molds. However, a normal furnace can simultaneously contain approximately fifteen flasks, for a significant recovery of productivity. Given the available instrumentation and the realization of more than one rubber mold, as it realistically happens in the case of series production, the estimated time for the injection of a single wax is 30 seconds.
We added ten minutes to this time for the assembly of each tree with a total weight of 500 g, of which 50% is production scrap in the form of sprue and feeders. With these times, in eight working hours it is possible to produce the maximum number of flasks that can fit in the considered furnace. At the same time, the caster is able to melt, pickle and cut the sprues of the 15 trees made on the previous day. Ultimately, every working day it is possible to obtain 3.75 kg of jewelry.

With direct investment casting, the process-limiting step is the phase of printing the waxes. Assuming that the printer is able to produce about 220 pieces of 10 g per day, while at the same time the trees can be assembled with the already prepared waxes and the metal can be cast inside the flasks, the estimated potential production capacity is about 2.2 kg of jewels per day. This value, however, is highly susceptible to the type of printer. For the present analysis, a multi-jet printer CPX 3500 plus (3D Systems) was considered.

Finally, with laser printing, the productivity is directly related to the printing time. In the case of 10 g rings on a single build platform with seven pieces per level and a total of five overlapping levels, a total of 350 g of jewelry can be completed in about 24 hours.

Table 13 Production capacity of the three examined techniques

Technique	Traditional Casting (kg/day)	Direct Casting (kg/day)	SLM™ (kg/day)
Daily Productivity	3.75	2.2	0.35

Table 13 highlights how the production capacity of the traditional production techniques is still higher compared to selective laser melting. It should, however, be emphasized that this high potential capacity is not always necessary and fully exploited in the field of fine jewelry, in which the casting equipment is often underutilized. In any case, for the production of large batches in hundreds and thousands of pieces, laser printing is not convenient in terms of economic cost, but only for series with a medium to low production volume. To date, unique pieces and niche collections remain the undisputed niche of SLM™ technology, besides special geometries that are only achievable by this technique.

3.8 Market Prices

In order to introduce, the incidence of costs for the implementation of a new production technique such as selective laser melting into daily production, we will now give a closer look to the economic aspect of the topic. An analysis of market prices and economic affordability really helps the operators in industry understand how a new technology is in fact an effective implementation and how it can be considered when selecting the most suitable manufacturing technique to use. It is also true that this choice depends on many factors, as previously explained, but it certainly involves the level of attention to the investments and the business budget plan.

For a proper evaluation of market prices it is important to consider that some relevant factors, such as the hourly cost of the operators and the electricity to power the plants, vary according to the concerned geographical area. For this reason our analysis refers to the Italian market, where prices are among the lowest in Europe, mainly because of low labor costs compared to other European markets such as those of France and Germany.

For each technique we defined a price range (Table 14), since the final value depends on several production yield factors such as optimization of the casting flasks and of the laser printing platform, the type of objects to create and the production scraps in terms of damaged pieces and feeders (in investment casting) and supports (in the case of selective laser melting).

Table 14 Market price for jewels produced with the three examined techniques

Technique	Market Price (€/g)
Traditional Casting	0.2–1
Direct Casting	2–6
SLM™	4–12

At the moment, it is evident that traditional investment casting is the most economical production technique of the three, using singularly less expensive machinery when compared to laser printers, and reducing the costs of some phases thanks to the high quantity of pieces simultaneously involved in the process. On the contrary, the costs and the market price of direct casting are much closer to those of selective laser melting.

The combined analysis of lead time, production capacity and market prices shows that the strengths of selective laser melting involve the production of unique pieces or limited series, for which the lead time compared to investment casting is essentially shorter, and the production of jewelry pieces which, for reasons of geometry or material, i.e., hollow objects with extremely reduced thickness or with three-dimensional lattices, is not otherwise obtainable with the typical casting techniques.

To conclude the study of the economic and productive convenience of selective laser melting with respect to the other techniques used in jewelry production, here is an interesting comparison between SLM™ and a different technology— chain production. The machines for the manufacture of the chains, similarly to the printers for selective laser melting, are used to produce pieces not otherwise obtainable with casting. With both techniques, realistic production demands a large number of machines capable of working simultaneously. This is to achieve, in the case of SLM, an increase in daily productivity, while in the case of chain production it is also needed for the production of multiple chain patterns at the same time. Indeed, unlike SLM, in which different types of objects can be produced simultaneously on the same platform, a chain machine can continuously produce only one kind of pattern at a time, while each modification requires the reconfiguration of the instrument by the operator. The purchase and maintenance of a high number of production machines, however, implies a considerable initial investment in capital equipment.

An analysis of the market price of a chain shows it selling for 0.4 to 0.6 €/g. However, it is immediately evident that the return on invested capital, despite a daily production capacity of about 2 kg per machine, is low compared with selective laser melting, which can produce 0.35 kg per day with average sales prices of 8 €/g. SLM™ then proves to be competitive when compared to the technology used for chain production, specializing in the creation of complementary items to those obtained by investment casting, once again granting higher profit margins and a rapid return on the invested capital to the jewelry maker, in addition to a versatility of use that is clearly at the exact opposite of the machinery for chain production.

3.9 Environmental Impact

The environmental impact is one area that is of increasing interest for every company. Respect for the environment and territory strongly contribute to sustainable growth of organizations in the whole world system. The Leading-edge companies recognize the importance of investing in sustainability by monitoring their impact. This allows them to manage performances in a conscious way and also to greatly reduce the final costs.

One of the universally recognized parameters for the assessment of a production process is the so-called Carbon Footprint (CF), which refers to the amount of greenhouse gases (GHG) emitted during the analyzed process, expressed in terms of CO_2 equivalent mass. The comparison of GHGs emitted by the three analyzed techniques was performed considering all the phases and the materials required to complete the production of 1 kg of jewelry. The same production steps and times used for the calculation of lead time in Tables 9, 10 and 11 were also used in this study.

The emission values caused by production and disposal of consumable were obtained from Ecoinvent 2.2 database,[14] while emission caused by electricity production is referred to the Italian electricity grid.[15] Equivalent production phases in the three techniques, like master alloy melting for investment casting and materials pre-melting before atomization for selective laser melting, were not considered for the technique comparison. The emission caused by the production of raw metal materials was similarly not calculated. Moreover, only greenhouse gases caused by the use of machinery and side plants during jewelry production, and not by their construction and maintenance, were considered.

In the case of traditional and direct investment casting, the emissions values for the burnout cycle of flasks reported in Tables 15 and 16 were calculated under the most advantageous scenario, i.e., a full furnace with fifteen flask. The calculation was made scaling the total emissions for this phase by the number of flasks needed to make 1 Kg of product, t i.e., flasks of a total of fifteen.

Table 15 Carbon footprint of traditional investment casting

Production Phase	**kg CO_{2eq}/kg**
Prototype Creation	7.39
Preparation of Rubber Mold	1.62
Injection of Waxes	0.31
Assembly of the Tree	0.07
Preparation of Flasks	0.72
Flask Burnout	15.90
Alloy Pre-Melting	0.44
Melting and Casting	1.85
Pickling	0.42
Cutting of Sprues	0.06
TOTAL (approx)	28.8

Table 16 Carbon footprint of direct investment casting

Production Phase	kg CO_{2eq}/kg
Printing of Waxes	3.70
Removal of Waxes Supports	0.64
Assembly of the Tree	0.07
Preparation of Flasks	0.72
Flask Burnout	15.90
Alloy Pre-Melting	0.44
Melting and Casting	1.85
Pickling	0.42
Cutting of Sprues	0.06
TOTAL (approx)	23.80

Table 17 Carbon footprint of selective laser melting

Production Phase	kg CO_{2eq}/kg
Atomization	1.64
Printing & Cleaning of Machine	13.2
Removal of Supports	0.03
TOTAL (approx)	14.70

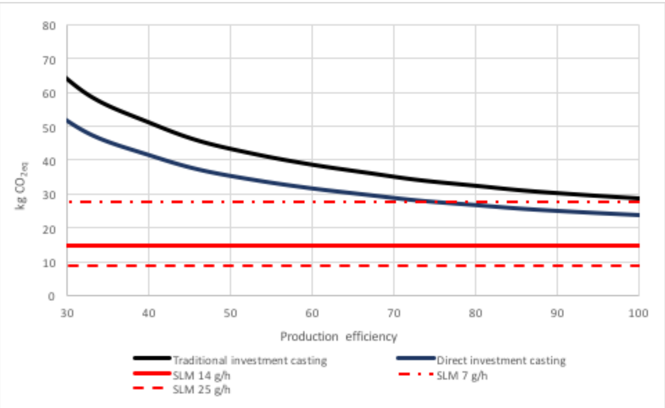


Figure 25 Trend of greenhouse gases emission with variation of production efficiency

The estimated production of greenhouse gases arising from the use of the three different production techniques shows that the emissions caused by selective laser melting are significantly lower than those caused by the other two technologies. It is also clear that, for all of the analyzed techniques, the biggest amount of greenhouse gas emission is caused by the production steps that use electricity for a long period of time—the flask burnout in classical and direct investment casting and the printing stage for selective laser melting.

The impact of the flask burnout cycle on emission values causes a great increase in the production of greenhouse gases per kilogram of jewelry if the furnace unit is not completely full. In this case, in fact, emissions are no longer distributed between the maximum number of flasks but between a smaller quantity. The emissions dependence from the production efficiency, i.e. the number of flasks in the furnace, is presented in Figure 25, with data already shown in Table 15 and Table 16 corresponding to 100% efficiency.

In the case of selective laser melting, the emission is instead dependent on the printing rate, which in turn depends on the geometry of the pieces and from the printing parameters. Figure 25 shows the emission value for the case analyzed in Table 17, corresponding to a printing speed of 14 g/h, and the values corresponding to 7 g/h and 25 g/h, representing the usual speed range for SLM technique.

It is immediately noticeable in Figure 25 that only with a very slow printing rate for selective laser melting and high production efficiency for investment casting does the greenhouse gas emission is become lower for casting. Generally, in fact, the amount of greenhouse gases produced by selective laser melting is much lower compared to the other two technologies, coming to be lower than half compared to traditional and direct investment casting when those techniques are used with low production efficiency, i.e., with semi-empty furnaces. To conclude, it is therefore possible to say that the SLM™ technique is almost always better compared to investment casting as regards the environmental impact of production.

4. CONCLUSIONS

Our past experience and constant research have enabled us to examine, in a critical and objective manner, the advantages and disadvantages of three major production techniques in the world of jewelry: traditional investment casting, direct investment casting and selective laser melting. For a schematic presentation of the overall performance analysis see Table 18. To each feature is a score is given: the more asterisks there are, the better performing is the technique is under that aspect. For example, a greater number of asterisks for "definition" means a better maximum resolution of the items produced, while a greater number of asterisks for "finishing loss" stands for a smaller amount of lost material. The radar chart in Figure 26, graphically representing the examined characteristics, is helpful to understand when the use of selective laser melting can actually be an advantage compared to traditional and direct investment casting.

Table 18 A comparison of the overall performance for the three manufacturing techniques

Aspect Measured	Traditional Casting	Direct Casting	Selective Laser Melting
Versatility of Materials	**	**	****
Flexibility of Geometries	**	***	***
Surface Quality	****	***	**
Definition	****	*****	***
Defects	**	***	*****
Mechanical properties	****	****	***
Finishing Loss	****	****	***
Production Capacity	*****	***	*
Market Price	*****	***	**
Lead Time (Small Batch)	*	***	*****
Lead Time (Series)	*****	****	*
Ecology	**	**	****

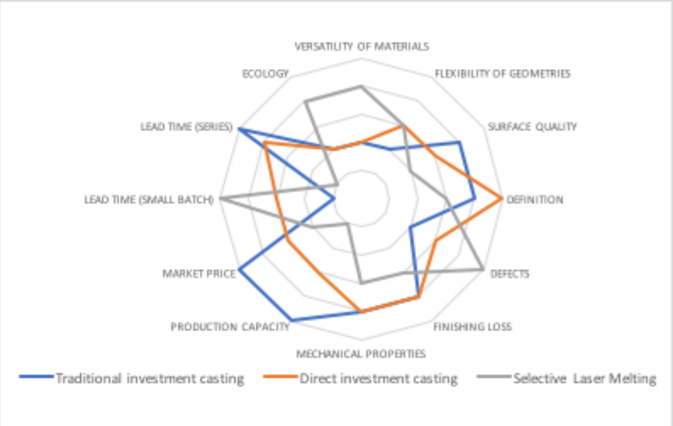


Figure 26 A comparison of the three production techniques

It is clear that selective laser melting is generally faster than casting when few pieces are to be produced, whereas in the case of series production, the higher production capacity of investment casting, especially the traditional one, makes it more competitive in terms of time. Market prices are also significantly lower with the latter technique, while direct investment casting and laser printing show almost equivalent values. Selective melting can still be advantageous, even in the case of series production, for the realization of particularly complex geometries or with materials otherwise difficult or even impossible to use in investment casting, thanks to the greater versatility of SLM™. Its higher production cost can be also compensated by the possibility of creating hollow objects, allowing a final price for the printed jewelry potentially even lower than that of traditional investment casting. The higher level of surface roughness obtained with selective laser melting, however, is the source of greater finishing loss. Ultimately, at least from a general point of view without considering a specific geometry or production need, selective laser melting is currently the technology offering the potentially highest versatility with respect to the other more traditional techniques.

As a conclusion to the present comparison, it is worth sharing our current vision of future. Several years ago we started exploring the possible uses of the SLM™ technology in jewelry, driven by a dream and fascinated by an innovative technique. After years of research, testing and actual production, we are still convinced more than ever of SLM's great potential as a productive technique in jewelry making. It is important, however, to choose the right technique depending on the type of production. Production using SLM is not the most convenient technique in all cases. As we have said, in fact, there are cases in which traditional investment casting is more convenient in terms of time and costs, as for example in the case of series production of technically simple jewelry pieces.

Although the SLM™ technique is still seen as experimental and limited to the big brands, in our vision of the future the gold industry will eventually use selective laser melting and investment casting equally. In fact, the higher cost of the jewel and the average longer production time can often be overcome by the higher geometric possibilities of SLM as opposed to traditional investment casting. With regard to direct investment casting, its versatility in terms of geometry as opposed to traditional investment casting has already been surpassed by the greater potential of the selective laser melting technique. SLM shows no negative consequences compared to direct casting such as to be considered more disadvantageous, so it is not unrealistic to expect that SLM will gradually replace direct casting in the near future.

In conclusion, traditional investment casting, with its legacy dating back into the mists of time, and selective laser melting, the result of contemporary technology, could soon start to coexist in an integrated way and perhaps "team up" in the very near future, opening up a new set of possibilities for jewelry manufacturers, both in terms of cost savings and innovative technical solutions.

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