Valentina Allodi
Progold S.p.A. – Trissino (VI) Italia

Valentina Allodi is R & D Specialist of Progold S.p.A, a company that produces precious and semi-finished metal alloys in gold, platinum and titanium obtained with direct 3D printing. A point of reference in the team for innovation and research on additive metal printing, Valentina graduated with honors in Science and Technology of Innovative Materials in 2010, subsequently completing her studies with the Ph.D. in Nanotechnology and Nanomaterials.
In 2011 she won a research grant at the University of Verona and worked with the same institution as a teacher and researcher until 2015.
In Progold she proactively contributed to the research project presented at the The Santa Fè Symposium 2016 international conference entitled **“Direct 3D Metal Printing: A Trip through New Opportunities and Innovative Alloys”** and participated in the next edition of 2017 with the research **“Why Should We Direct 3D Print Jewelry? A comparison between Two Toughts: Today and Tomorrow ”.**

As part of the fourth industrial revolution, direct printing of precious metal jewellery deserves constant analysis of the current state of the art to understand whether and when a jeweller should favour this technique over classic lost wax casting methods.
In recent years, our research programme has included studying printing strategies, support techniques and a general analysis of the chemical and physical characteristics of the precious powders used. With this study, we are looking at technological evolution with a more practical and operational eye, sharing our experiences and giving an honest analysis of both the good and bad aspects of 3D jewellery printing, trying to define when and why it is convenient to print jewellery items.

“Jewelry and direct 3D printing: the start of a new era?“

Valentina Allodi
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INTRODUCTION

Manufacturing processes in the gold and jewelry sector have essentially not changed for hundreds of years with no real revolutions in how jewelry is made. Only in more recent decades have some twentieth century technological inventions, including electroforming, CNC processing, rapid prototyping, laser welding and Metal Injection Molding, been acknowledged in the goldsmith world and integrated into the production chain, resulting in incisive innovations.

These innovations have sometimes been introduced to improve old and traditional manufacturing processes, which are still widely used due to their unquestionable effectiveness, without opening up any new production paths. In other cases, however, the use of technological innovations has totally revolutionized the production process, something which would have been unthinkable a few decades ago, through the use of completely different manufacturing mechanisms to those of existing methods.

Selective laser melting comes within these latter techniques that have totally and radically changed the production rules.

Compared to classic jewelry manufacturing, selective laser melting (SLM™) is an extremely young technology generated by a collaboration between the Fraunhofer Institute in Aachen and F&S Stereolithographietechnical GmbH in 1995. The commercial distribution of the first printers began a few years later in 2000, thanks to collaboration with MCP HEK GmbH, then named SLM™ Solution GmbH, and currently sharing the technology with Dr. Matthias Fockele’s Realizer GmbH. The SLM™ technique differs from selective laser sintering (SLS™) in that the particles are totally melted by the laser beam instead of surface welding, due to the effect of the temperature.

Unlike laser melting, lost wax casting, a key manufacturing procedure in the jewelry sector, boasts an age-old origin and its first usage in serial production dates back to the early Bronze Age (3000-3500 BC). Since the dawning of this technique, the creation of items has always required a model to be re-produced, created separately in manually moldable material, thus establishing at the very start, the impossibility of directly producing the items devised by the artist or craftsman.

Although there are many lost wax casting techniques, each one implies considerable complexity due to the production of rubber molds, assembling the tree and casting the refractory moulds for alloy pouring, not to mention the notable environmental impact due to wax combustion gases and the disposal of refractory materials.

Overcoming these disadvantages, together with the constant possibility of improving metal alloys, making them void of gas porosity, shrinkage and foreign inclusions, and exploring new possibilities in geometric and usable material terms, were the driving forces that induced Progold S.p.A. to experiment the new selective laser melting technology in the jewelry sector, opening up new scenarios aimed at resolving the typical problems of casting.

Over recent years, Progold S.p.A.’s effort to integrate selective laser melting into the jewelry industry has been carried out through the selection of optimal printing parameters, precious and non-precious alloy composition, tolerance types and comparative studies between SLM™ and traditional casting performances in creating critical jewelry elements, i.e. articles with reduced thicknesses, hollows items and decorative details like pavé and ajour. These steps along the way have been shared over the last five years through articles of a purely technical-scientific nature, focused on numbers and experimental results.

What has been decided to do at this point, is to stop, raise the observation point, look at the technological evolution with a more practical and operative eye and journey through the experience gained over the years and then to deal, point by point, with the many and diverse moments of comparison between selective laser melting and the main production techniques. A journey that began eight years ago and is able to highlight how SLMTM printing can be considered as one of the most significant revolutions that the jewelry industry has experienced in the last few decades, as well as give a practical answer to a question that, for many, is still in the air: when and why does direct precious and non-precious metal jewelry printing make sense? The first study in this direction, presented in this article, compares direct metal 3D printing with both the classical casting method - the reigning technique in the jewelry sector in terms of versatility - and direct casting.

COMPARING TECHNIQUES

CASTING AND MODELING MECHANISMS

The analysis carried out to outline the strong and weak points between casting and selective laser melting must initially undergo a clear and immediate understanding of the respective modalities through which both lead to the melting phase of the material and its modeling into the desired shape.

In fact, how can the added value of one over the other be acknowledged if the key mechanisms of both processes are not initially understood?

In classic and direct casting, the melting process is simultaneous for all the material, which must fill the mould channel during pouring. The alloy must therefore be completely heated to the optimal temperature, a process that is generally obtained in the industrial field with the use of special furnaces and crucibles.

In selective laser melting (SLM™), on the other hand, the increase in temperature needed to overcome the alloy's melting point is provoked by the interaction between the radiation of a thin laser beam and the material to be melted. Therefore, melting in a given instant is extremely localized and only involves a small area around the beam's irradiation point. The alloy becomes solid very quickly as the laser continues its scan and therefore, the quantity which, instant by instant, is involved in the melting moment, is minimal. The items increase by adding solid material, without the macroscopic movement of masses of molten metal.

Given the above differences, it is obvious how the characteristics of the material used for creating the jewelry item can be crucial in casting yet not so in selective laser melting, or vice versa. In the case of casting, for example, whether traditional or direct, the melting temperature of the alloys used plays a fundamental role in the feasibility and costs of the process. In fact, materials with a high melting point, like palladium, platinum and titanium alloys, require casting machines with components able to tolerate high temperatures and metal reactivity as well as a special coating for creating refractory molds.

Moreover, the use of ceramic crucibles and molds implies the risk of contaminating the alloys to be melted, yet another source of inclusion and hard point defects in the items produced. In the case of titanium-based alloy casting, for example, the problem of contamination from crucibles is so significant that other, often more expensive, metallurgical techniques are favored for jewelry manufacturing, such as, cold crucible arc melting (1). In any case, the problems linked to the need to considerably raise the temperature of a consistent mass of material remain, such as inhomogeneous thermal distribution within the molten material, heterogeneity due to segregations in the solid state, the vaporization of some elements or their reaction with residual oxygen.

With laser melting, however, the temperature required for melting the alloy is reached by localized interaction between the laser beam and the material. The alloy absorbs photons emitted by a laser source, whose energy is then converted almost instantly into heat. The first fundamental parameter for estimating the efficiency of the melting process will therefore be the absorbance of the material being melted at the particular wavelength of the laser used. In the case of selective melting processes, the laser being used is typically close to infrared with wavelengths centered at 1064 nm (Nd:YAG) or 1070 nm (Yb fiber). The material's capacity to absorb the radiation must be assessed in the region of the infrared.

The main obstacle of melting metals with lasers is their high reflectivity, i.e. the radiation is reflected by the surfaces of the material rather than absorbed. This effect, directly correlated to the high electrical conductivity of the materials concerned, is particularly evident in the case of gold, silver and copper. In fact, these elements maintain a greater than 97% reflectivity, even when wavelengths are practically invisible. Other elements used in jewelry are less problematic from this point of view, like, for example, platinum or palladium, which have reflectivity values of 74.5% and 80% respectively (2).

A second discriminating parameter for selective laser melting efficiency is the material's thermal conductivity. Once part of the radiation has been absorbed, the sample acquires thermal energy which can disperse at various speeds for conduction towards the adjacent areas.This implies a more localized re-heating for materials with low thermal conductivity coefficients and a more widespread re-heating for alloys with a higher thermal conductivity towards adjacent areas to the detriment of the temperature reached by the area directly struck by the laser.

In the case of metals, it is generally known that thermal conductivity is proportionate to electrical conductivity and temperature. Therefore, once again, elements like gold, silver and copper are at a disadvantage compared to other materials due to their high thermal conductivity (Table 1), which, together with their high reflectivity, means that a greater laser energy is required to melt their alloys compared to palladium, platinum and titanium.

One of the strategies used to increase laser absorption efficiency in the selective laser melting of gold was to add small quantities of semi-conductor elements, like germanium or silicon, which lower the material's electrical conductivity (3) (4).

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

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

Electrical conductivity, in fact, directly influences reflectivity and thermal conductivity, in that, the more the metal is electrically conductive, the more it will reflect the incident radiation and conduct heat. In any case, despite the qualitative improvement obtained with this compositional doping, the efficiency difference in the selective laser melting of gold alloys compared to that of intrinsically more absorbent and less conductive metals is still high, even for metals that have a decidedly greater melting temperature. One striking example is given by the traces produced by laser melting with identical parameters in a 950 platinum alloy and an 18-karat red gold alloy with the addition of germanium (Figure 1). In this case, the same quantity of energy supplied to the materials produces a profoundly different result: a thin and irregular trace in the case of red gold and a thicker, more coherent line in the case of platinum. For all the analyses that follow, gold and platinum alloys with a karat size of 750% and 950% were taken as reference.

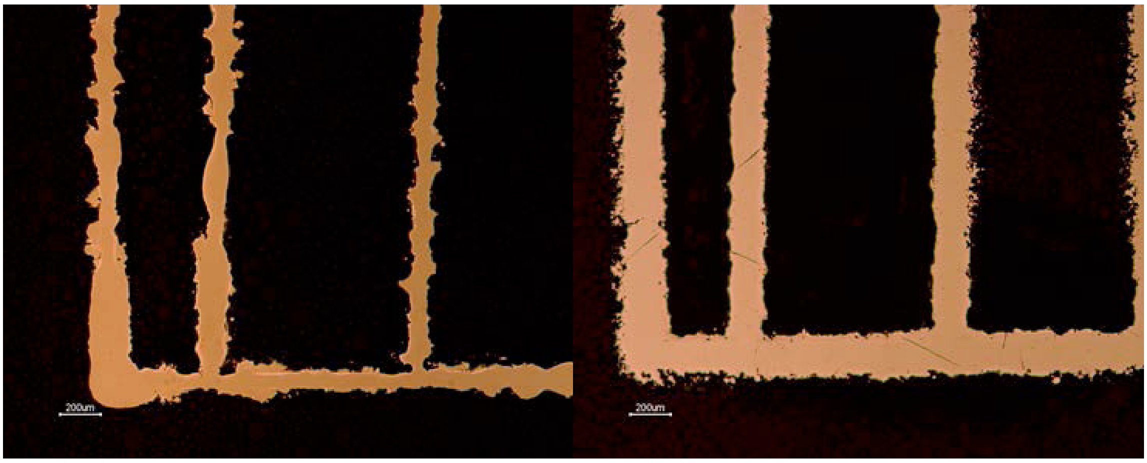


Figure 1. Single traces printed with a 62.5 watt laser power and 0.33m/s scan speed: red gold (left), platinum (right)

With selective laser melting, it is therefore possible to see a reversal in the energy convenience of alloy melting compared to casting so that printing jewelry in platinum and titanium is energetically more efficient than printing jewelry in gold or silver.

This is one of the great peculiarities that make the technique an authentic revolution. It is not, in fact, uninteresting for any jewelry producer to have the chance to diversify its goods offer on the market with collections produced in metals that are difficult to work using traditional techniques. A specific reference is 950 platinum and the difficulty of creating jewelry with complex and articulate shapes in this material (Figure 2). Titanium is among the non-precious materials that is particularly suited to selective laser melting due to its intrinsic characteristics and is a material that has recently aroused the interest of jewelers due to its hardness, bio-compatibility and the possibility to color it using an anodizing process.

And so, many new frontiers have opened up for all jewelry producers, who are always in search of a new and cutting edge product to offer on the market. Designers are finding new inspiration and can feel more at liberty to conceive shapes that, until now, were practically impossible to achieve.

Figure 2. Bracelet and ring made in 950 platinum alloy using SLM™ printing. Heart bracelet and ring, Designer: Xin Xin Zhou, IED Turin – Jewelry and Accessories Design Course

To be more specific, we will better examine the differences caused by typical SLM™ selective and localized laser melting and lost wax casting. The extremely thin dimensions of the metallic layers melted by laser and the high solidification speed of the metal result in averagely small-sized crystalline grains that are generally smaller than those obtained in casting the same metal alloy (Figure 3), with a consequent improvement in mechanical resistance (5). Moreover, the intrinsically small grains in selective laser melting make using grain refiners in the alloy composition unnecessary with the consequent elimination of some of the typical segregation and hard point defects that can occur when refiners are used.

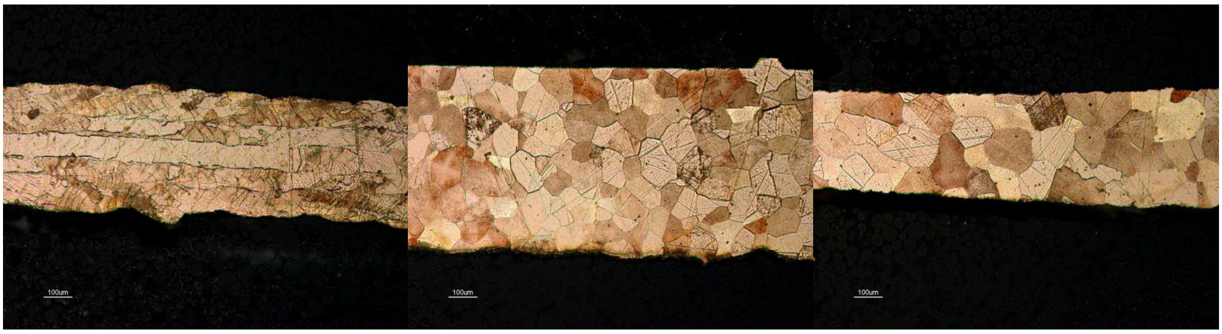


Figure 3. Micro-structure of an article in yellow gold alloy, obtained with SLM™ (left), classical casting (center) and direct casting (right). In the case of SLM™, the average grain size found was 30 micrometers while in casting, it was around 90 micrometers (5)

GEOMETRIC LIMITATIONS

HOLLOW OBJECTS

In addition to the differences between casting and selective laser melting dictated by the various metallurgical processes, the refractory mold used in the casting process with the entire chain of necessary operations for making it and filling it with metal, geometrically limits jewelry production. Selective laser melting overcomes these limits. An example is given by the impossibility of producing internally hollow monolithic jewelry that is more or less isolated from the outside.

In the case of classic casting, the limitations of this family of objects are already triggered in the wax model production phase. With this technique, the ways of obtaining jewelry with cavities, even if they always connect to the outside, and with controllable wall thickness, foresee the use of a hydrosoluble wax core inside the rubber mold, which is then dissolved before preparing the cylinders (6) (7) or a separate injection of the two halves of the hollow object and subsequent welding of the waxes.

The hydrosoluble wax obliges designing specific holes in the jewelry item's walls in order to dissolve it rapidly with water as well as the creation of a robust rubber support followed by another in plaster to tolerate injection pressure. These holes in the metal walls prevent making entirely closed hollow objects. In direct casting, the problem of producing hollow items persists, even though resins can be built with cavities that are almost totally isolated from the outside since they are obtained with an additive printing technique, so that, in the subsequent cylinder production phase, the liquid coating is not able to penetrate into the internal cavity unless there are an adequate number of holes. In fact, the liquid ceramic paste must be able to reach all the areas that the wax model does not occupy in order to guarantee a perfect reproduction. In this case, this also implies the obligation of inserting a high number of holes to allow easier access to the refractory inside the jewelry. These openings are also needed to support the positive core of the cavity and to totally eliminate the refractory once casting has been done. A typical practical solution to get round the limitations imposed by hollow jewelry casting starting from the combustible materials (wax, resin), is to cast the parts of the item separately and then weld them together. Welding, however, leads to additional problems as well as the need for further manufacturing procedures. The problems generated in this case are linked to the need to hide the joins which can often be of a color that does not match the adjacent material, especially in the case of red gold, whose chromatic conformity with the welding alloy clashes with the need for lower melting temperatures. Furthermore, the heat of the welding process leads to tension in the thermally altered area especially in the case of self-hardening alloys, which can cause deformations and breakages. Lastly, there is still the real risk that, in the case of fine thicknesses, welding may provoke the accidental melting of a larger area of the jewelry item.

With selective laser melting these problems diminish and, in the construction of hollow articles, the only necessity is to make a limited number of tiny holes to let out the powders trapped inside the item thus obtaining, without any particular manufacturing problems, hollow shapes that are practically completely closed, like the wedding bands shown in Figure 4 and the ring in Figure 5 which demonstrate how the internal cavity can be filled or left empty with reticular structures to increase the mechanical resistance. The ability to produce articles with closed cavities is a universally recognized strong point of laser printing and offers the chance to reduce the final weight of the item in relation to its overall dimension which is of equal apparent volume. A practical application of this possibility will be illustrated in paragraph 4.4.

Figure 5. white gold, hollow ring made with and without reticular supporting structure.

THICKNESSES

The phases required for creating a wax or resin model, for producing ceramic coatings and casting the molten alloy lead to yet another limitation regarding jewelry design with the casting method: the thicknesses.

Producing the model is problematic in the case of fine thicknesses because injecting the wax into the rubber molds can often become difficult. Filling the fine thicknesses often requires high compression of the wax, therefore the rubber tends to swell and produce thicker or deformed models. Rubber molds can certainly be optimized to make filling easier by decreasing load losses and wax cooling speeds with a structure of feeders together with the use of waxes with better filling properties (8). Nevertheless, models with fine thicknesses are then always considerably difficult to extract from the molds and irreparable distortions and dimensional changes are a frequent occurrence.

In the case of direct casting, the use of additive manufacturing makes the model production phase much less critical, even if an appropriate choice of polymeric materials, de-waxing cycle, printing technique and parameters is still fundamental in obtaining high quality castings with no resin residues that may obstruct the narrow spaces to be filled (9). However, in both techniques, pouring the molten metal into the refractory mold, which must ensure that all the finest details of the item are filled, is still a critical moment. The thinner and larger the channel to be filled is, the more difficult it is to fill due to the inevitable and drastic thermal exchange between the refractory and the molten alloy, whose surface tension can further prevent the metallic flow.

The lowest thickness limit of the material that can be obtained in casting, irrespective of any optimization in model architecture, is hard to define precisely because it depends on the size of the thin area and the overall geometry of the item, even if it is typically thought to be around 0.3-0.4 mm in the case of filigree and about 0.4-0.6 mm in the case of walls for classic casting and 0.2-0.4 mm for walls and 0.2-0.3 mm for filigree in the case of direct casting, always bearing in mind that, the larger the thin areas are, the more difficult it is to fill them completely. In any case, reaching and possibly exceeding these limit values, as long as the item's overall geometry permits it, requires considerable technical and technological effort using complex feeding systems, increased overheating of the metal and plaster temperature and excess gas pressure in the pouring to increase the material's filling capacity. These changes in the process, however, still lead to negative consequences, such as greater reactivity between the plaster and the molten alloy and a higher risk of coating breakage due to the greater pressure and the consequent presence of refractory inclusions or the desired shapes not being produced. Moreover, finer thicknesses significantly increase the percentage of production rejects since the number of incomplete items on the cast tree containing tens of articles can drastically increase and the successful production of one single item cannot be considered as a success in serial production.

With selective laser melting, fine thicknesses and complex structures are not a limiting factor since no wax model or filling of a refractory mold is required. The lowest metal wall limit is given by the thickness of the single laser melting trace, compatibly with preserving the adequate robustness that the jewelry item needs. The minimum thickness of the melting trace obviously depends on the type of laser printer, the construction parameters and the type of metallic powders. In our case studies and for gold, platinum and titanium alloys, the minimum thickness is in the range of between 0.1 mm and 0.2 mm. Moreover, thanks to the localized melting of the material, the overall geometry of the piece had little impact on the thicknesses and the smallest sections, which can even extend over the entire volume of the jewel.

This peculiar characteristic has, in our experience, allowed us to successfully print rings with extremely thin walls, achieving 0.2 mm in the larger areas of the item with no problem, even in the rough state, as in the case of the ring printed in titanium in Figure 6, and three-dimensional reticular structures, like the ring in Figure 7, which show the natural extension of the two-dimensional structures of filigree without the limitations imposed by the process of filling a mold.

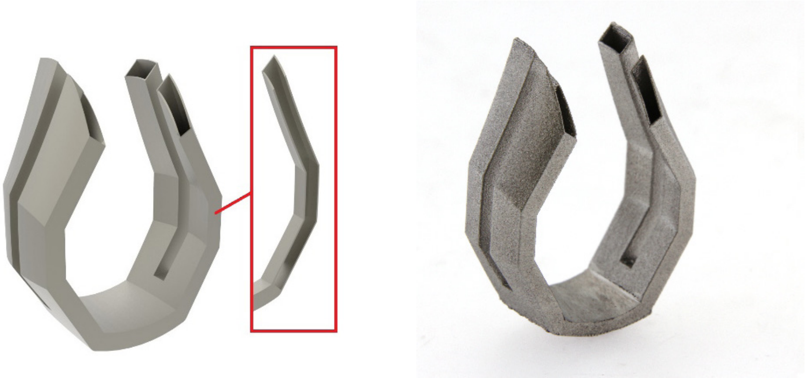


Figure 6. Digital model (left), section of the model with extension of the thin areas (center) and photograph of the printed titanium ring with a wall thickness of 0.2 mm.

Figure 7. Rings printed in red gold with extensive three-dimensional reticular structures, with and without full internal walls.

Think here about how this could be another significant revolutionary element. It is not only a new way of designing and conceiving shapes, it is also a way to optimize precious metal investments. Jewelry, which by nature is a fundamental element of acknowledgment in what is being increasingly defined as a consumer society, has always played a considerably important role in a person's look. Playing with thicknesses is certainly determining, whatever the amount of material used to make the item, and provides the opportunity to wear an ornament and voluminous accessory of significant aesthetic impact, giving authority to the shape without having to pay for the high specific weight of the precious material. This topic will be dealt with more deeply later.

DEFINITION AND DIMENSIONAL COHERENCE

The thickness of a single printed trace in selective laser melting, besides representing the thickness of the smallest achievable wall, is, more generally, the resolution limit of this technique on the construction platform plane (X-Y). In exactly the same way as in the artistic design of an item of jewelry, it is not possible to create details of a smaller dimension than the trace of the pencil used to design them. This leads to a worse definition on the construction plane (X-Y) with selective melting compared to that which can be obtained with classic casting, if the protrusion of the decorative details is limited to a few tenths of a millimeter. Over these protrusion values, in fact, in the case of casting, the filling problems already mentioned in paragraph 2.2.2 occur, so, the values of the smallest thicknesses, and therefore of the details that can be reproduced, inevitably increase and lead to a worsening in resolution. On the other hand, in the case of selective laser melting, the smallest obtainable thicknesses only depend on the width of the molten trace and not on the extension of the thin area. The maximum definition obtainable on the X-Y construction plane remains constant whatever the geometry of the item being reproduced. As for direct casting, the resolution depends on the system used to produce the resin or wax model, but, in general, especially in the case of printing with resin, and again with details with a protrusion of a few tenths of a millimeter, definition can be even greater than that obtained with classic casting.

It should be noted that definition in selective laser melting is much greater if plane z is taken into consideration: in this case in fact, resolution depends on the height of the single printed layer, which in SLM™ can reach values of 20 micrometers, 10 times less than the width of trace on the XY plane.

Moreover, due to the thickness of the molten trace, in SLM™, in order to respect the nominal dimensions of the items, the printing software must use a compensation, stopping construction before reaching the geometric borders of the item to avoid oversizing (Figure 8). In other words, the more external laser scan corresponding to the contours of the item is never carried out, otherwise the dimensions of the end product will be greater than required. The scan is therefore carried out further in at a distance corresponding to half of the melting trace to compensate the intrinsic thickness.

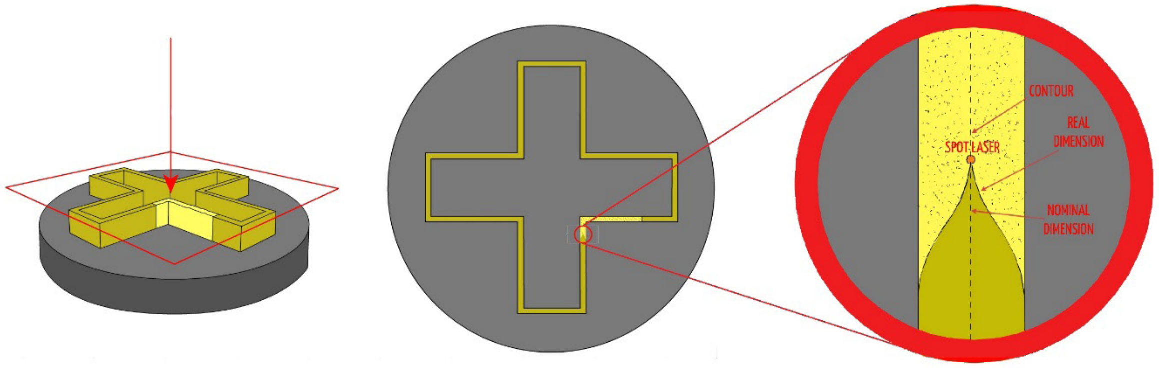


Figure 8. Intrinsic thickness of the melting trace and effects on the real dimensions of the items.

The dimensional non-conformity of the items is largely caused, in both casting and selective melting, by the shrinkage of the material as the temperature decreases. This, however, happens in different ways depending on the technique used. In casting, solidification regards the entire piece simultaneously and implies a certain dimensional variability according to the position of the pieces on the casting tree, for example, since the position of the thermal core can change considerably. On the other hand, the mechanical stress caused by shrinkage can be partially eliminated by how long the metal remains at a high temperature in the molds. In the case of selective laser melting, solidification occurs in layers, causing a preferential development direction of the residual mechanical stress. The low construction temperatures do not eliminate this stress which can deform, break or even rip the items off the platform. One way to limit the effect of this stress is to opportunely establish the position of the items on the construction platform. On the other hand, the independent growth of each item and the construction graduality guarantee greater dimensional constancy.

SUPPORTS AND FEEDERS

Besides the above examples, a complete comparison between the advantages and disadvantages of selective laser melting and casting techniques must also take into consideration the presence of supports in one and feeders in the other. These elements are indispensable for fixing the growth position of the jewelry in one case and for introducing the metal alloy into the hollow shapes in the other.

With laser printing, supports are also needed to sustain the item's jutting parts which might otherwise be easily knocked away by the movement of the brush that distributes the metallic powder and disperses the heat generated during melting. The shape of the supports and their position is decided on in such a way as to make the removal of the items from the construction platform easier and economic. They are prevalently three-dimensional and reticular with an extremely fine point of contact on the item. Just as with the feeders used in casting, the support frameworks are a precious part which must be eliminated from the jewel and therefore their quantity is a factor that must be taken into account in the general economy of the manufacturing process, since they are included in production waste. Compared to the feeders in the casting trees, support frameworks are in general less important than the precious metal used in the production process and therefore the loss in laser printing is usually less than that in casting. It must however be noted, that particular jewelry geometries can require a supporting framework that would make the ratio between item volume and support volume disadvantageous.

Supports are also generally required for the wax or resin model in direct casting but, in this case, they are eliminated prior to producing the ceramic molds and are therefore not on the assembled tree. Their only impact in the production process is the time it takes to remove them and they have no effect on the quality of the item and on waste.

An important difference between supports and feeders is their dependence on the volumes of the jewelry to be produced. In casting, voluminous items require huge feeders to move the thermal core out of their volume to avoid shrinkage porosity for which there is also a limit to the maximum thickness of the items achievable in the classic refractory coatings, given the typical dimensions of the molds. The casting containers for lost wax casting usually take a maximum refractory mold of less than two kilograms inside a steel cylinder with a diameter of between 10 and 15 cm and height of between 10 and thirty cm. Therefore, the maximum thickness of obtainable items is around 5-10 mm. Furthermore, in these cases, item feeding can be a higher fraction of the total mass, causing very high production waste and an extremely low number of jewelry items produced in each cylinder, greatly lowering the process's usually high productivity and consequently raising costs. In selective laser melting, the size and number of supports is only linked to the surface size of the items. In this case, production waste in terms of supports is not increased when manufactured mass is increased, since it is linked to the overall surfaces of the item rather than its volume.

The main inconvenience linked to the presence of supports in selective melting is due to their removal. In fact, some residue from them can stick to the printed jewel or there tiny craters can appear from tearing the material attached to the support ends. The entity of these defects and the possibility of eliminating them in the finishing phase depends on the type of support used. The more solid they are, the more difficult it is to remove them, which also increases production process loss (Figure 9).

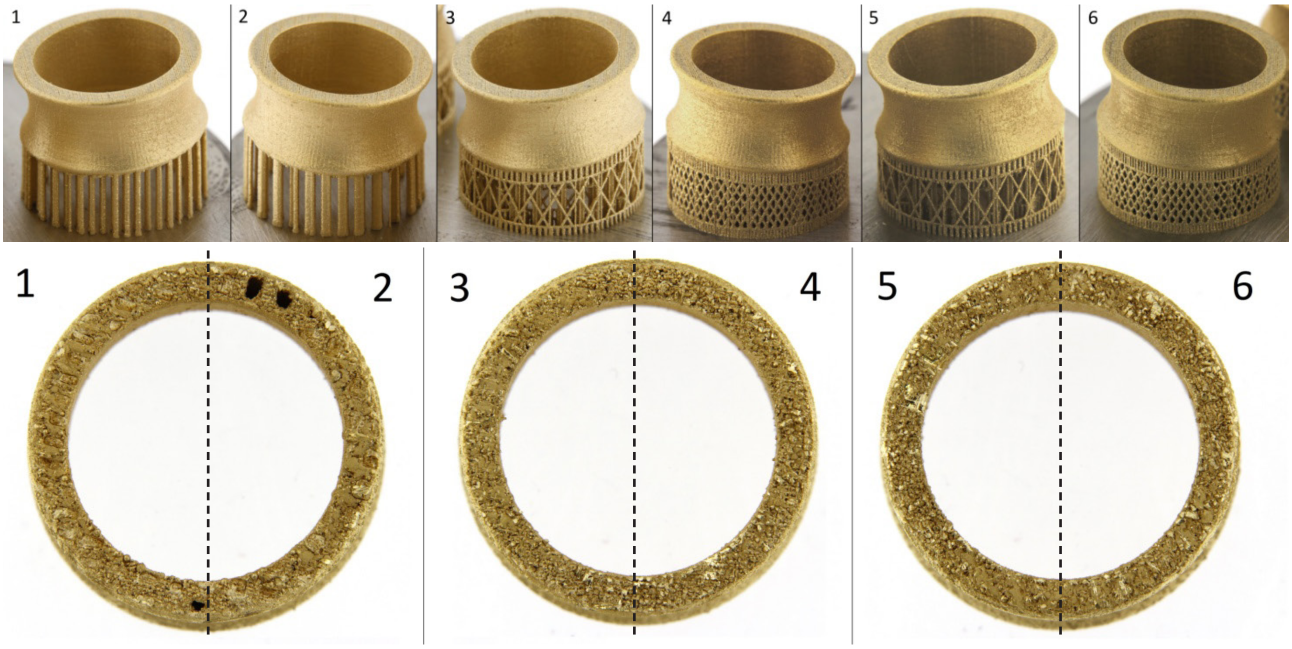


Figure 9. Hollow rings printed with different types of support and appearance of the lower surfaces after the supports are removed by hand. Holes left from removing columnar supports can be seen in areas 1 and 2.

For any item of jewelry, deciding on the right support is a compromise between the least invasive and the best function in terms of structural support and thermal dispersion. In fact, as in casting when incorrect feeding can lead to shrinkage, filling and breakage problems, an inappropriate support in selective melting is the source of other manufacturing problems. For example, if the supports are too far apart or too thin, sliding, shifting and overheating can occur compromising the final quality of the item. If, however, the support is too big, the roughness of the surfaces it is attached to can be excessive and hard to eliminate.

All materials have a critical angle in the horizontal above which introducing supports during item printing is not required since the inclination of some surfaces is high enough to act as a support, thus saving time and material. For this reason, the user's ability plays a fundamental role in achieving the best possible quality by selecting the item's orientation on the printing platform in such a way as to minimize the surfaces in contact with the supports. Some of the problems relating to inadequate supports can be seen in the examples in the photograph in Figure 10, in which a too weak support led to its breakage and the consequent incompleteness of the printed item. If the area is inadequately supported, a lack of material in these areas can usually be observed with effects that range from spongy-looking surfaces to actual holes. Figure 11 gives an example of a titanium item that was inadequately supported with evidence of the lack of material in the area whose nominal diameter should have been the same as the supported area.

Figure 10. Example of support breakage on a white gold item

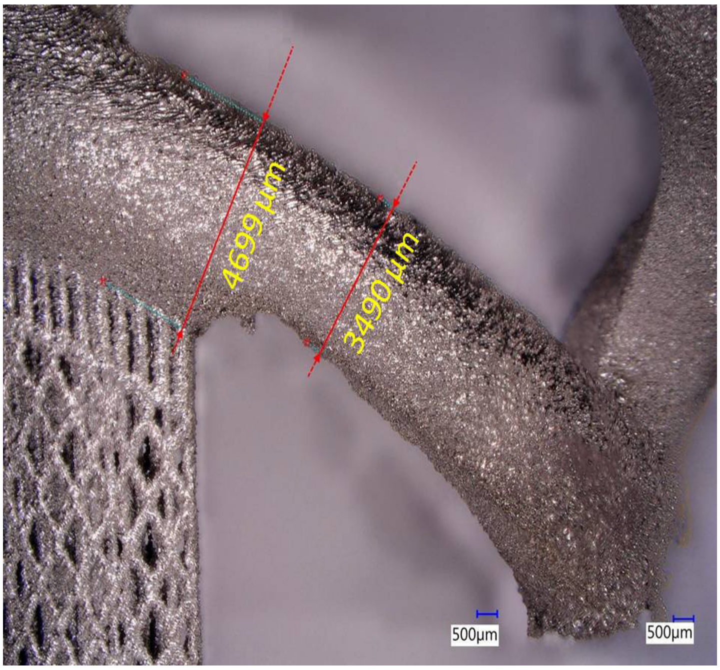


Figure 11. Printed titanium ring with insufficient supports

The obligatory presence of a certain quantity of supports obviously affects the design of printable items. When small-sized decorative details or stone-setting elements are entailed, as shown in Figure 12 for binary stone-setting, the residue left by the supports is often incompatible with the level of definition required, resulting in printed jewelry of unsatisfactory quality.

Figure 12. Example of a ring unsuitable for 3D printing

Jewelry with geometries particularly suitable for selective laser melting includes items in which all the surfaces have a greater inclination than the material's critical angle so that minimal support will be required. An example of a ring corresponding to these criteria is shown in Figure 13, where support was only needed at the lower points of the item in order to attach it to the construction platform.

Figure 13. Ring with particularly suitable geometries for selective laser melting due to the minimum quantity of supports needed in its production.

DEFECTOLOGY

Despite the differences imposed by the materials and design of the jewelry, the different physical principle connected to the production of items is the source of another important difference found in jewelry produced with one technique or the other and regards the type of micro-structural defects created in the metal alloys. A general analysis of the defects that can occur in an item obtained by casting does in fact reveal that the majority are caused by mainly chemical-physical processes that occur during the production phases, while, in the case of laser printing, the defects are prevalently physical since there is no interaction between wax, mold, crucible and molten alloy. This is the main cause of their notable diversity, whether in terms of nature, shape or localization within the jewelry items. The main types of microscopic defect typically found in classic and direct casting are porosity from shrinkage and gas, hard points due to refractory inclusions, grain refiners, inter-metallic compounds, graphite inclusions from the crucibles and carbon residues from waxes.

Shrinkage porosity is due to the change in volume that occurs after material solidification because the alloy has a considerably different density in its liquid state than in its solid state. If, after solidification, it is not possible to produce more liquid to fill the holes left by the volume change, these holes will be visible as porosity. The incidence of this complex defectology is therefore linked to the effective variations in volume and the speed at which the alloys in the mold cool in regard to it being possible to use the still molten metal to feed the critical zones. Metal alloy shrinkage or, more rarely, expansion, is an inevitable intrinsic process of metal going from a liquid to solid state which can be limited by appropriately formulating the composition of the alloy or mainly concentrating it in the feedheads by means of a calibrated choice of casting connections. Thanks to the different construction mechanism in selective laser melting, that is, by layers rather than simultaneous, this type of defect does not generally occur. In selective laser melting, porosity can be found due to a lack of material in an incomplete melting, the origin of which may be due to an incomplete melting of the powder in the single laser trace (Figure 13a) or an incorrect distance between adjacent traces (Figure 13b).

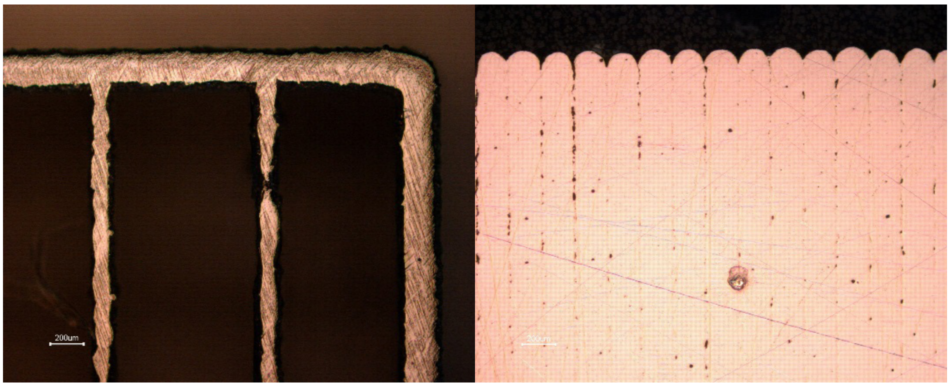


Figure 14: a) Trace with incomplete laser melting, b) porosity due to the imperfect melting of adjacent traces

Gas porosity, however, can occur in both casting and selective laser melting but for different reasons. In casting, gas porosity defects are either caused by the decomposition of the plaster cast due to contact with the molten alloy at a high temperature and, in this case, the holes are mainly located in the surface areas of the items, close to the interface between the plaster and metal, or by evaporation of the alloy components. In selective laser melting, on the other hand, the gas in this porosity is generally argon that became trapped during the turbulent melting process or released from the partial and temporary vaporization of metals which, in printing conditions, produce excess vapor tension(10). These holes do not generally have any specific distribution but can occur throughout the item. One example of gas porosity in selective laser melting can be seen in Figure 15 where round cavities are clearly visible in the center of the traces produced by single laser scans.

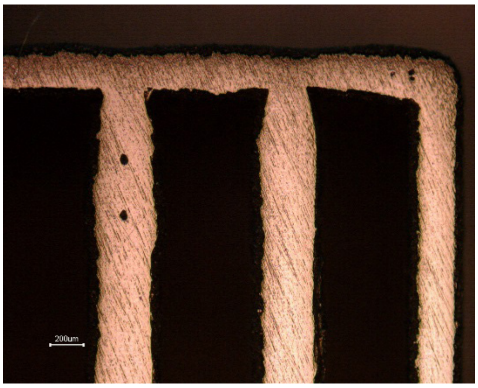


Figure 15. Porosity due to gas in single printed traces

Defects linked to the presence of foreign materials incoherent with the metallic base are another vast family of imperfections that can be found in jewelry manufacturing. In lost wax casting, refractory inclusions due to coating and graphite abrasions caused by decaying crucibles, are very frequent and damaging. These defects derive from the traditional use of molds and crucibles and are therefore totally inexistent in selective laser melting. Other types of foreign inclusions typically found in casting are inter-metallic hard points or grain refiners, which are expelled by the base metal because of compositional imperfections or an incorrect cooling process. In laser printing, these latter inclusions are quite rare because the cooling speed is so fast that any crystalline nuclei have no time to form and because refiners are typically absent.

As for inclusions due to contamination, these can potentially occur in both casting and selective laser melting. In the case of casting, besides an incorrect usage of the scrap, contamination can happen if the same crucibles are used for casting different alloys, a problem that can be totally avoided simply by using different crucibles for each different alloy. In selective laser melting, this possibility is much more problematic. If a laser printer is not cleaned properly, when changing the alloy inserted into the machine, contamination can easily occur between the powder previously loaded into the printer with consequences that range from item fragility to non-conformity of the gold fineness. Changing the material being worked is much more difficult in selective laser melting than in casting because of the complex cleaning process of the printers. In jewelry, where items are usually produced in different alloys but in limited numbers and fixed compositions, one solution to this problem is using several printing machines, with one for each particular precious alloy.

In addition to the defects mentioned so far, there are other problems that can only be found in casting which derive from one phase more in the production process compared to selective melting, i.e. the creation of a wax or resin model used for the subsequent production of the mold. The defects here can be incomplete filling, bubbles and surface irregularities in the wax model, or residues linked to not removing the wax, and especially the resin, correctly.

Going on to macroscopic defectologies, concentrations of solidification shrinkage can occur in casting with extremely evident formation of neck-ins in item section or cracks due to segregation at grain boundary in low melting point or fragile phases as well as a lack of material due to the molds not being completely filled. In selective laser melting, on the other hand, collapses and a lack of material

can occur due to incorrect support as well as cracks and deformations due to internal stress.
These latter defects are due to the growth mechanism of the items in SLM™, by which the item grows in consecutive layers, accumulating mechanical stress due to material shrinkage after cooling. In general, this stress, which can be released by subjecting the items to thermal relaxation treatment, can cause the supports to break (an effect already seen in Figure 10), item delamination or deformation. The latter can lead to variations in size compared to the design and curvature once the supports are removed.

COMPARING PERFORMANCES

VERSATILITY

In recent developments in jewelry produced with laser printing, the technique has shown surprising capacities to overcome some of the obstacles found in using precious materials in classic lost wax casting. In the latter case, the limitations imposed by the casting temperatures and the reactivity of the materials limit the number of structural elements that could potentially be used in precious metal alloys to about ten metals, with the addition of a few other additive elements for regulating the microstructure, such as grain refiners and hardening substances.
This limitation considerably restricts the level of mechanical and optic performances that a precious alloy may have, but the use of selective laser melting has led, at least in part, to the recovery of new characteristics due to the possibility of alloying elements which, in classic casting, are extremely reactive and refractory (11). One example is the use of niobium and titanium at grades that are practically prohibited for classic casting (19% and 16%, Figure 15), by selective laser melting mixtures of metallic powders and achieving a premium yellow index. Moreover, in the case of titanium, due to its low density, exceptionally light (12.0 g/cm3) gold alloys (18kt) have been obtained, which is about 25% less than a white palladium alloy. One inconvenience of these innovative alloys is currently in controlling the gold fineness since many refractory metals can interfere considerably in the fire assay.

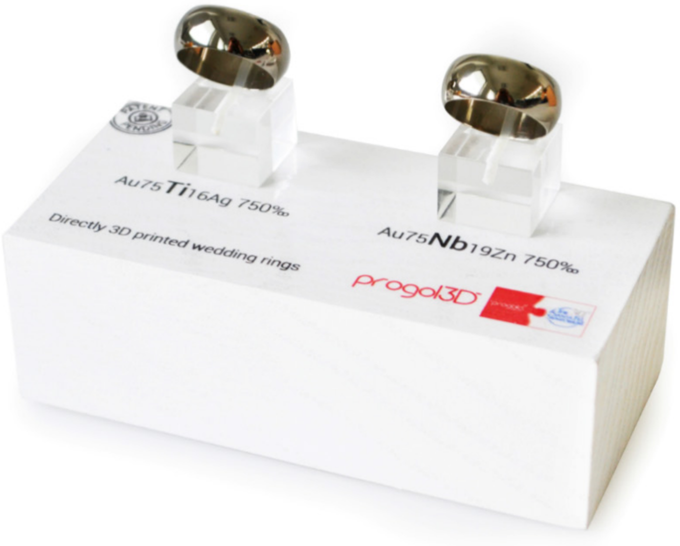


Figure 16.White gold wedding bands (18kt) with 16%p Ti and 19%p Nb.

QUALITY: DENSITY AND ROUGHNESS

In recent years, several studies have been carried out by the research and development laboratory at Progold S.p.A. with the aim of comparing the qualitative level of jewelry produced with selective laser melting, classic casting and direct casting (5) (12) (13). It emerged from the results obtained that the fundamental characteristics for assessing the quality of jewelry are density and surface roughness, parameters that are then directly connected with robustness and definition.
The density of the items produced is, in reality, a direct or indirect measurement of the residual porosity, a defect that makes it considerably difficult to create surfaces worthy of an item of jewelry. In addition to Archimedes's widely used indirect method of measuring porosity, which is really only sensitive to occluded holes in the material, in our studies we preferred a direct measurement, carried out by digitally analyzing images of sample sections under an optic or electronic microscope to assess the area affected by porosity in relation to the total area studied.
The results obtained by comparing the residual porosity in laser printed items and items produced by classic or direct casting, generally always highlighted, with the same alloy, a greater final density with selective laser melting (12) (5). With the same simple ternary alloy (AuAgCu), the porosity of an item made with laser printing is about twenty-five times less than that made with classic or direct casting (Table 2). A significant divergence from this trend was observed in the case of the same alloy modified with gallium, which did, in fact, improve the characteristics obtained in classic and direct casting but significantly worsened the quality of the alloy produced by selective laser melting, mainly due to the intense projection of particles during its construction, fatal for the regular construction of an item. Because of this, the residual porosity measured in this case was less in casting (0.05%) compared to laser printing, although the measured value was still higher than that recorded in selective laser melting with the alloy devoid of gallium (0.01%).

Production method	Au-Ag-Cu alloy porosity (%)	Au-Ag-Cu-Ga alloy porosity (%)
Classic casting	0.25	0.05
Direct casting	0.25	0.05
SLM™	0.01	0.47

Table 2. Residual porosity in 18kt gold alloy with classic casting, direct casting and SLM™ (12).

In the same way as density, roughness has also been the object of widespread studies, involving, over the years, different alloys and items with different surface inclinations. For our studies, we chose to consider the parameter of total roughness (Rt) of the profile, corresponding to the difference between the highest point and the lowest point on the surfaces, as a reference value for comparing the techniques. This parameter is, in fact, the thickness of precious material which must be removed in the polishing phase to obtain a perfectly smooth and aesthetically satisfying surface.

The results of the various analyses carried out always showed greater roughness in the items produced by laser printing due to the intrinsic growth method of this technique. Moreover, roughness decreased in going from items produced by direct casting to those made with the classic casting method. It should, however, be highlighted how, in the case of direct casting, the final roughness depends on the type of prototype machine used. In this study, the machine was a multijet printer for wax, which was favored over a resin printer due to it having less carbon residues after dewaxing and a greater final roughness compared to stereolithographic printers. The results obtained for an 18kt yellow gold alloy, with roughness measured on the surfaces at different angles compared to the horizontal plane, are summarized in Table 3.

Production method	Min Rt (μm)	Max Rt (μm)	Average Rt (μm)
Classic casting	10.8	39.9	22.0
Direct casting	18.6	44.9	27.3
SLM™	22.1	59.1	31.3

Table 3. Minimum, maximum and average roughness of 18kt yellow gold samples after classic casting, direct casting and SLM™ (5) .

MECHANICAL CHARACTERISTICS

Mechanical properties, typically obtained by traction and hardness tests, influence some of the key characteristics for producing jewelry and for the finishing process, as well as the final performances of the articles. In general, higher elongation and breaking strength values imply the material's good plasticity and make it easier to set stones. A good hardness, on the other hand, implies greater wear, tear and scratch resistance as well as a more secure stone setting.

In our previous research works, we presented a comparison between the mechanical properties of items produced with SLM™ and classic casting using yellow and red gold and platinum. Table 4 shows the results for an 18kt white gold palladium alloy after production, with no further thermal treatments. The samples used for this comparison had chemical characteristics and the same palladium content but were optimized for each of the production techniques in question. For example, the casting alloy contained a grain refiner. Both alloys used are available on the market and are currently used for making18kt white gold jewelry.

Production method	Yield strength (MPa)	Breaking strength (MPa)	Elongation at breakage (%)	Hardness (HV)
SLM™	344 ± 28	460 ± 39	21 ± 8	154 ± 2
Casting	283 ± 14	480 ± 25	33 ± 9	174 ± 5

Table 4. Mechanical properties for 18kt white gold palladium alloys during casting and SLM™

The comparison between the samples tested showed a slightly lower hardness in SLMTM production, while the breaking strength values were similar. Elongation at breakage was, however, higher for items made with casting, as had already been observed in the past with yellow and red gold alloys and platinum alloys. These values show that an item produced by casting is more malleable with a possible reduction in the risk of it breaking while, for example, stones are being set.

FINISHING LOSS

Finishing loss is mainly connected to the total surface roughness of the items produced which represents the minimum thickness of material to be removed in order to obtain a compact and shiny surface. In the case of casting, the maximum roughness is in the range of 40 and 45 micrometers for classic and direct casting respectively, while for SLM™, the roughness value is greater, consequently a greater thickness needs to be removed in the polishing phase.

A comparison between the finishing losses of identical objects printed with SLM or cast is not really very legitimate since selective laser melting is a technique normally used to produce items that cannot be cast. Nevertheless, to give an idea, a theoretical calculation of the precious metal lost in finishing is shown in Table 5, carried out considering the red gold wedding band with a density of 14.84 g/cm3 in figure 17.

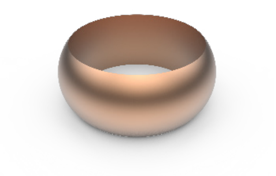


Figure 17. Digital model of the ring used for calculating finishing losses

Production method	Thickness lost in polishing (mm)	Relative volume (cm^3)	Loss (g)
Classic casting	0.040	0.055	0.8
Direct casting	0.045	0.062	0.9
SLM™	0.060	0.082	1.2

Table 5. Polishing losses calculated in casting and SLM™, in volume and weight terms

It should be noted that the losses indicated are calculated for excess in that the volume removed is considered entirely full, while in reality, surface roughness means that only the crests are the material parts removed in the first layers, which will increase in density nearer to the full part of the item. The data show how, in the case of classic and direct casting, the loss is less than in selective melting. The impact of the supports, which varies depending on the dimensions of the surfaces supported, should also be taken into consideration in this latter technique. As explained earlier, the surfaces supported can have surface defects in terms of additional or missing material which often requires more polishing in those areas. In the case of casting, it should however be pointed out how the underlying porosity, more common than in selective laser melting, can make further polishing necessary to achieve the quality required in high jewelry with the consequent loss of a greater quantity of precious metal.

THICKNESSES, VOLUMES AND WEIGHT CONTROL IN SELECTIVE LASER MELTING

It was previously highlighted how one of the added values of the selective laser melting technique compared to casting is the possibility of producing hollow objects with thin and reticular walls. Table 6 gives a short summary of the geometric limits of the different manufacturing techniques, already discussed above.

Technology	Wall thickness limit (mm)	Filigree thickness limit (mm)	Hollow items
Classic 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

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

If using SLM™, jewelry items can be designed which, with the same volume, are much lighter compared to those obtained with classic or direct casting because of their hollowness, with the consequent saving of precious metal. Moreover, thanks to the possibility of creating three-dimensional grids, strengthening structures with a low-impact on the weight can be inserted inside the cavities to increase mechanical resistance. An example of the reduction in weight that can be obtained by producing hollow objects rather than solid ones is shown in Table 7 for the ring in Figure 18.
In the case of a hollow structure, without the addition of strengthening grids, the weight variation calculated going from a solid ring (obtained with classic or direct casting) to rings with increasingly thinner walls, is shown in Table 7 in the case of a platinum alloy.

Figure 18. Digital model of a ring used for the calculations shown in Table 6

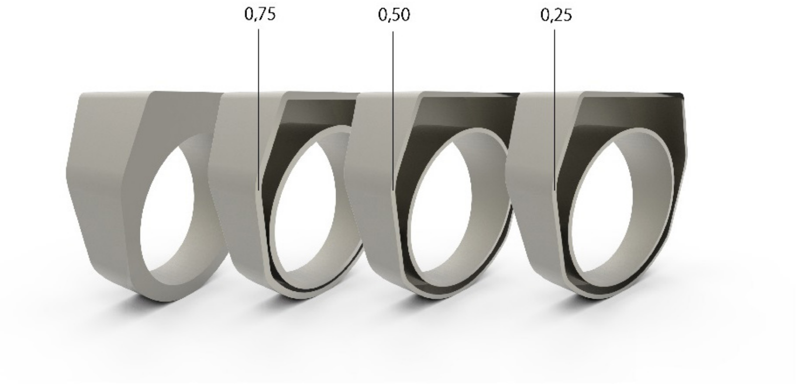
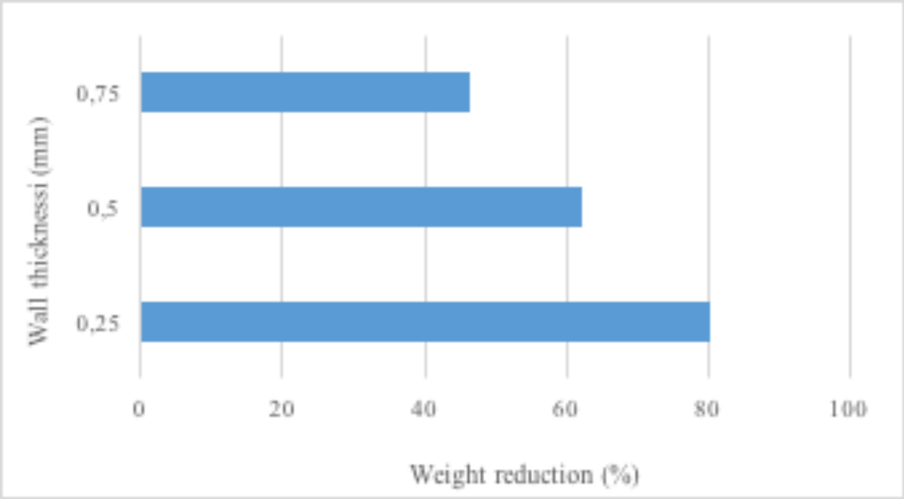


Figure 19. Digital model of the ring at various levels of hollowness

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

Table 7. Variations in weight based on the thickness of the wall for rings in platinum

Figure 20. Weight reduction after progressive emptying of the items in SLM™



It is possible to see from the data how a reduction in weight equal to about 50% can be obtained for platinum using a 0.75 mm wall thickness and a saving of over 80% in weight can be achieved with 25 mm walls.

Emptying can also represent a way to make high volume jewelry, which otherwise would be excessively heavy, easier to wear. In casting, as already explained, an almost entirely closed hollow jewelry item can only be obtained by producing the two halves separately and then welding them together. Figure 21 shows examples of high volume, hollow rings, obtainable with SLMTM without welding.

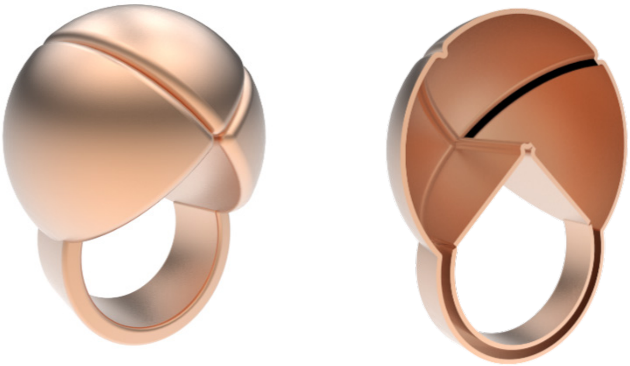


Figure 21. Model of a high volume ring

Besides the reduction in weight to increase wearability, emptying the rings can also be used for another purpose, i.e. to modulate the thickness of the external walls of the item so as to obtain the same final weight in different measures of the same model. This is an advantage when the price of the ring to the public is set for a given model and not calculated according to the weight, as happens in high jewelry. In fact, producing an article in casting, the maker either increases the quantity of the precious material used for large-sized rings or the thicknesses must be reduced to increase the size, changing, however, the external aspect of the ring. In the case of SLMTM, on the other hand, the internal thicknesses of the ring can be modified, compensating the overall increase in volume in the case of greater measures with the increase of the internal cavity and thus obtaining items with a constant metallic weight and volume for the whole range of available sizes.

Table 8 shows a possible example for the ring in Figure 22, printed in yellow gold. The ring was emptied and the thickness of the walls was modified according to its size, obtaining a practically constant weight (Figure 21). For reference, the weight on solid ring measurement variation is also shown.

Figure 22. Variation in the wall thickness according to the ring size

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

Table 8. Variations in the weight of the different sizes of the solid ring and the ring with variable wall thickness

PRODUCTION LEAD TIME

The time needed to deliver an order naturally depends on the number and type of items to be produced. However, from a comparison of different production techniques, it immediately appears obvious how, not only is the production time for a given number of items different, but, considering different sized lots, the production time calculated for one technique is very different to the other.

The comparison between classic casting, direct casting and selective laser melting was therefore carried out considering three case studies, that is, the production of one, ten and one hundred gold rings. The items used for the production time comparison had, with the same alloy, a volume and consequently an identical mass of around ten grams, while the shape changed in accordance with the technique used. The shapes were chosen using a typical geometry generally produced with each of the techniques in question, more specifically, a band ring for the classic and direct casting techniques and a hollow ring for selective laser melting. In this way the time simulation was carried out on jewelry that, due to their shapes, would realistically be produced with one technique rather than the others under examination.

Lead time calculation was carried out considering the typical production times in high jewelry, a jewelry market segment in which production with selective laser melting is particularly suitable due to its innovative potential. The production capacity analysis presented in the following paragraph was therefore carried out with this sector in mind.

The initial model planning and design times were not taken into consideration in the calculation since they are steps that all three techniques have in common. Production machinery availability was considered as the same for each type, therefore the calculation of production and process productivity times was prepared assuming the presence of just one machine for each phase of the work per company, therefore one wax injector, one wax jet printer, one machine for preparing the cylinders, one annealing furnace, one casting machine, one laser printer, and so on. The production capacity for each device corresponded to the average on the market, therefore, in the moral doubt of differences between the various techniques, machinery with exceptional performances were excluded in order to keep in mind companies' variable degree of purchasing power. For each of the techniques examined, the times required to complete each production phase, summarized in the tables below, were calculated. The prototype creation phase in classic casting includes the creation of the wax model, its casting in non-precious metal and surface finishing. In particular, the use of a wax jet printer was considered for creating the wax model. In the wax preparation phase, the wax injection times, cooling and extraction times and item checking times were added together and amounted to about one minute for a shape of low complexity. Likewise, complex or more solid shapes require much longer preparation times. Lastly, wax preparation time can be further reduced if a second mold is created to be used while the wax in the first mold is cooling. Nevertheless, in the case in question, even for the production of one hundred items, the time saved in preparing the waxes is more than taken up by preparing a second rubber mold and was therefore excluded from production time calculation. Printing times in direct casting were estimated foreseeing the use of a multijet Projet CPX 3500 plus (3D Systems) printer.

Classic casting			
Production phase	**Work time 1 item (min)**	**Work time 10 items (min)**	**Work time 100 items (min)**
Prototype creation	1150	1150	1150
Rubber mold preparation	120	120	120
Wax injection	1	10	100
Tree assembly	1	3	33
Cylinder preparation	30	30	45
Cylinder annealing	720	720	720
Alloy pre-casting	15	15	15
Casting and pouring	15	15	60
Pickling	5	5	20
Smoothing	0.25	1	10
TOTAL (approx)	2050 (34.0 h)	2070 (34.5 h)	2270 (37.5 h)

Table 9. Estimation of production times with classic casting

Direct casting			
Production phase	**Work time 1 item (min)**	**Work time 10 items (min)**	**Work time 100 items (min)**
Wax printing	260	270	710
Support removal	60	60	90
Tree assembly	1	3	33
Cylinder preparation	30	30	45
Cylinder annealing	720	720	720
Alloy pre-casting	15	15	15
Casting and pouring	15	15	60
Pickling	5	5	20
Smoothing	0.25	1	10
TOTAL (approx)	1100 (18.5 h)	1120 (18.5 h)	1700 (28.5h)

Table 10. Estimation of production times with direct casting

Selective laser melting			
Production phase	**Work time 1 item (min)**	**Work time 10 items (min)**	**Work time 100 items (min)**
Digital model supporting	15	15	15
Printing and machine cleaning	110	440	4400
Removal of items and supports	3	30	300
TOTAL (approx)	130 (2.0 h)	480(8.0 h)	4700 (78.5 h)

Table 11. Estimation of production times with selective laser melting

Production technique	**1 item (hours)**	**10 items (hours)**	**100 items (hour)**
CLASSIC CASTING	34.0	34.5	37.5
DIRECT CASTING	18.5	18.5	28.5
SLM™	2.0	8.0	78.5

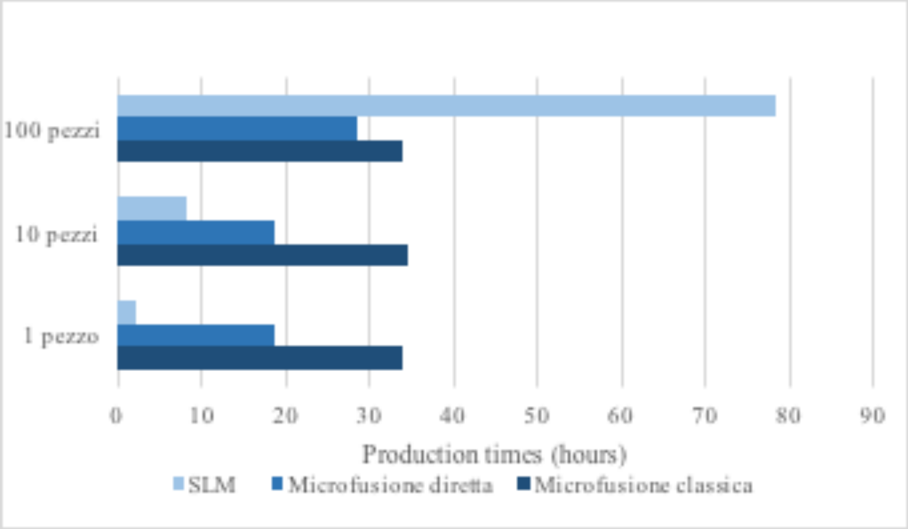


Figure 23. Production lead times for the three techniques based on the number of items to be produced

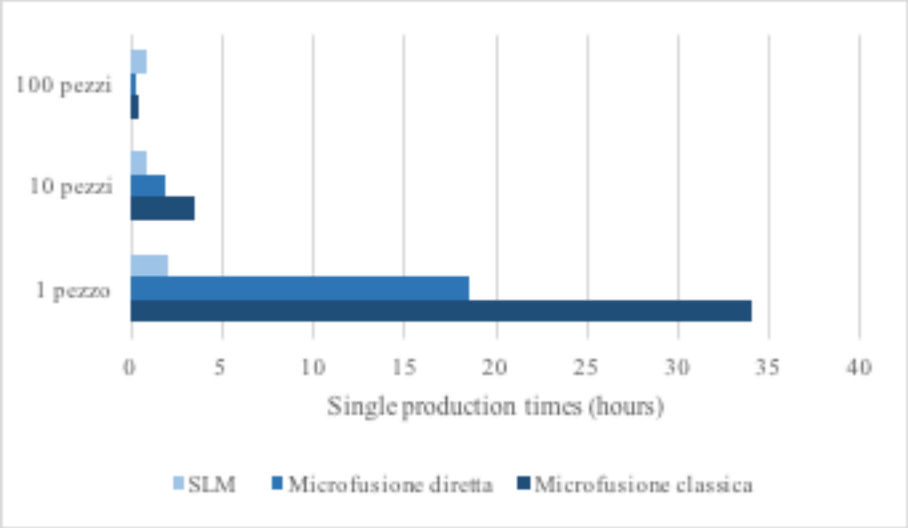


Figure 24. Production times by single object according to the production technique and number of items to be produced

In recent decades, lost wax casting has become the leading technique in jewelry production thanks to its manufacturing flexibility. Nevertheless, comparing production times in the case of classic casting, direct casting and laser printing, it can immediately be seen that, for producing orders of just ten items, the production time with selective melting is clearly less than with the other techniques. For a few items, the longest production times were found with classic casting because creating the prototype has a highly significant impact on the overall number of work hours. It is therefore obvious why, in reality, producing just the one piece with classic casting is a rare event, only justifiable for items of enormous artistic importance, and, in general, in this case, direct casting is the chosen technique. When re-producing an old series, for which the prototypes and rubber molds are already available, the production times of one or ten items with classic casting are considerably shorter, even less than direct casting, but still higher than selective laser melting because of the long annealing times required for the refractory coatings. The situation is the opposite in the case of having to produce about one hundred items. In this case, the lengthy laser printing times exceed the times required for prototype creation, ceramic coating annealing and wax printing, making casting generally faster than selective laser melting. For one hundred items, classic casting times are still greater than direct casting due to the lengthy prototype preparation times. If the number of items produced is further increased, the ratio between the times switches: the prototype production time needed in classic casting is in fact nullified and the wax printing times, longer than injection times, make direct casting more disadvantageous. In the case analyzed, to produce 225 items, equal to nine complete cylinders, production time was already 43.5 hours for classic casting and 45 hours for direct casting, a difference that increases as the number of items increases, simulating the production of a large series of jewelry.

The advantage in production speed shown for a relatively low number of items can be very useful in a world where originality and personalization has become a cornerstone for every company. One only has to look at the motoring, clothing and watch industries. This mass market phenomenon inevitably also affects the gold and high jewelry industry. In the past, trusted goldsmiths occasionally made a unique jewelry item for a single buyer, while nowadays, with laser printing, it is always possible to offer the same service much more rapidly. In fact, selective laser melting, unlike direct casting, can directly create a single and original article in precious alloy without putting an entire production cycle into motion. Furthermore, with the ability to create extremely light jewelry, maintaining or even increasing the overall volume, selective laser melting can produce highly striking items that are not uncomfortable or heavy to wear. However, in the case of jewelry to be produced in series, the production advantage of casting over selective melting is still evident. In this case, the use of the selective laser melting technique can be justified for an item's critical geometries (i.e. thin walls, extensive grids, cavities) or for materials with casting problems, like platinum or titanium, or in the case of particular economic advantages, like hollowing out the items to reduce the weight, or the possibility of keeping the weight constant while varying the size of rings and bracelets.

If, for example, the needs of the designers or creative artists were considered, there is now the possibility to receive effective serial production tests within a few hours. It is certainly revolutionary to think of such a creation speed and this strongly effects the entire jewelry distribution chain. One need only think about the need to supply stores and sales points with limited series of jewelry in a short time. For collections featuring a limited number of items, unique or niche pieces, selective laser melting revolutionizes any traditional lead time cycle, considerably shortening the most time-intensive production phase.

PRODUCTION CAPACITY

Production capacity is one of the most relevant aspects for a correct benchmark. Production capacity means the quantity of jewelry produced every day and has been defined as equal to the mass of items produced daily, as established by traditional industrial standards. The tools available were once again considered jointly by type and average production capacity, with the number of daily working hours set at eight, with no night shifts. Moreover, one single operator was considered for each production department, therefore, in the case of classic casting, for example, the wax technician was able to prepare the waxes, trees and plaster casts and, at the same time, the caster was able to furnace the plaster casts, do the casting and smoothing. In the case of operations involving automatic machinery, these were considered as able to work until the end of the production cycle, even outside normal working hours. For classic casting, one single annealing furnace can, on average, complete just one casting cycle during the working day because of the lengthy process of dewaxing the coatings. Nevertheless, a typical furnace can simultaneously contain about fifteen cylinders and this leads to significant productivity recovery. Given the equipment available and considering more than one rubber mold for the production of waxes, as realistically occurs in serial production, the time estimated for injecting one wax model was 30 seconds. Ten minutes for assembling the tree with an overall weight of 500g, of which 50% is production scrap due to the feedhead and feeders, were added. With these times, in 8 working hours, the maximum number of cylinders that can fit in the type of furnace considered can be produced.

At the same time, the caster is able to cast, pickle and smooth the 15 trees made the day before. In conclusion, 3.75 kg of jewelry can be obtained every working day.

As for direct casting, the limiting step of the process is the wax printing phase. Assuming that the printer is able to produce about 220 10-gram items a day and considering that, at the same time as printing, the trees with previously prepared waxes can be assembled and cylinder casting carried out, the potential production capacity was estimated at around 2.2 kg of jewelry per day. This value is, however, highly dependent on the type of printer used. For this analysis, the use of a multijet CPX 3500 plus (3D Systems) printer was assumed.

Lastly, in the case of laser printing, productivity is directly linked to printing times. In the case of rings of about 10 g, one single printing platform with 7 items per level and a total of 5 levels was completed in about 24 hours, amounting to 350 g of jewelry per day.

Production technique	Classic casting (kg/day)	Direct casting (kg/day)	SLM™ (kg/day)
Daily productivity	3.75	2.2	0.35

Table 12. Production capacity of the three techniques examined

Table 12 highlights how, in terms of production capacity, the traditional production techniques are still better compared to selective laser melting. It should, however, be underlined how this potentially high production capacity is not always necessary and fully exploited in the high jewelry field where casting systems are often under-used.

In any case, the production of large lots of articles, in hundreds and thousands of items, is not convenient using a laser printer if looked at purely in economic and cost terms, but for series with a medium-low production volume, it can be. To date, unique items and niche collections are the indisputable stars of SLMTM with the exception of particular shapes that can only be achieved with this technology.

MARKET PRICES

For the purposes of bringing into everyday practice the cost incidence of activating a new production technique like selective laser melting, we will now take a closer look at the economic aspect.

An analysis of market prices and economic convenience greatly helps sector operators to understand both the new technology and its effective implementation and how much it should be taken into consideration when deciding on the best production technique to use. It is also true that this decision depends on many factors, as seen above, but the investment aspect and its effect on the company budget, surely deserves attention.

In order to correctly assess market prices, it is important to consider how some factors that affect prices, like the hourly cost of labor and the electricity used to power the systems, vary according to geographical area. For this reason, our analysis refers to the Italian market whose prices are among the lowest in Europe, mainly due to the low cost of labor compared to other European markets such as France and Germany.

A price differential was identified for each technique, depending on the final value of the production yield, such as cylinder employment in the case of casting and the laser printing platform in SLM, on the type of item to be produced and the amount of scrap in terms of damaged items, casting feeders and supports in the case of selective laser melting.

Production technique	Market price (€/g)
Classic casting	0.2-1
Direct casting	2 - 6
SLM™	4 – 12

Table 13. Market price for jewelry produced with the three techniques in question

In general, classic casting is obviously the most economic production technique at the moment compared to the other two, using machinery which are singularly less expensive than laser printing and beating the costs of some of the phases thanks to the high number of items that can be processed simultaneously. The costs and market prices for direct casting are, on the other hand, much closer to those of selective laser melting.

From a combined analysis of lead times, production capacity and market prices, it can be deduced that the strong points of selective laser melting are firstly its ability to produce unique items or limited series, whose production times compared to casting, are substantially lower, and secondly, the creation of items whose geometries or the material used, cannot be produced with the classic casting method, like, for example, hollow items or pieces with extremely fine thicknesses or three-dimensional grids.

To conclude the study on the convenience of selective laser melting in economic and production terms compared to the other techniques used in jewelry manufacturing, an interesting comparison is SLM with chain production, a different technology to casting.

The machinery used for making chain, like selective laser melting printers, are used to produce articles that cannot be obtained with casting. With both techniques, a realistic production is entrusted to a high number of machines able to function at the same time. In the case of SLM, this strategy aims at increasing daily productivity while, in the case of chain production, this reason is joined by the possibility of manufacturing several model types at the same time. In fact, unlike SLM printing, in which different types of objects can be produced on the same platform, a chain-making machine works continually to produce one type of chain at a time and an operator has to reconfigure the machine in order to make any modifications.

The purchase and maintenance of a high number of machines, however, implies a considerable initial investment and ties up a large amount of capital.

From an analysis of the market prices of chains, which result as being approximately between 0.4 and 0.6 €/g, it is, however, immediately clear how the return on invested capital, despite the daily production capacity of about 2 kg per machine, is low compared to selective laser melting which is able to produce 0.35 kg a day with average sale prices of 8 €/g . The latter technique is therefore competitive if compared to the technology used in chain production, guaranteeing the producer higher profit margins and a much faster return on invested capital, as well as a versatility of use poles apart from chain machines.

ENVIRONMENTAL IMPACT

Environmental impact is increasingly becoming one of the areas of interest for every company. Respect for the environment and the territory contribute strongly to sustainable growth, not only for the company and sector but for the entire global system. It is well known how cutting edge companies recognize the importance of investing in sustainability by monitoring their own impact. This allows them to manage their performances in a conscious manner and also notably reduce the costs defined as “current expenses”.

One of the universally acknowledged parameters for assessing the environmental impact of a production process is the so-called Carbon Footprint (CF), which refers to the amount of greenhouse gas (GHG) released during the process in question expressed in terms of equivalent CO^2 mass.

A comparison of the GHG released by the three techniques analyzed was carried out considering all the phases and materials in the company required to produce 1 kg of jewelry, referring to the same steps and production times used to calculate the lead times in Tables 9, 10 and 11. To calculate gas emission caused by the production and disposal of the materials used, the data were taken from the EcoInvent 2.2 database, while for electrical power, the data used refer to the Italian electricity network (14). The processes considered as common to all three techniques were not included in the comparison, specifically, mother alloy melting for casting and the pre-casting of materials before atomization for selective laser melting. Moreover, neither emissions caused by the production of metallic raw materials nor emissions caused by the construction and maintenance of machinery and collateral systems, like for example, the water supply system and the air system, were calculated, although the emissions caused by their production use were. In the case of classic and direct casting, the emissions in the table for the cylinder annealing phase were calculated in the most advantageous manner. i.e. considering the furnace when full and re-scaling the phase’s emission by the number of cylinders needed to make 1 kg of product, in other words, four out of fifteen cylinders.

Carbon footprint for classic casting	
Production phase	kg CO_{2eq}/kg
Prototype creation	7.39
Rubber mold preparation	1.62
Wax injection	0.31
Tree assembly	0.07
Cylinder preparation	0.72
Cylinder annealing	15.90
Alloy pre-casting	0.44
Casting and pouring	1.85
Pickling	0.42
Smoothing	0.06
TOTAL (approx)	28.8

Table 14. Carbon footprint for classic casting

Carbon footprint for direct casting	
Production phase	kg CO_{2eq}/kg
Wax printing	3.70
Support removal	0.64
Tree assembly	0.07
Cylinder preparation	0.72
Cylinder annealing	15.90
Alloy pre-casting	0.44
Casting and pouring	1.85
Pickling	0.42
Smoothing	0.06
TOTAL (approx)	23.80

Table 15. Carbon footprint for direct casting

Carbon footprint for selective laser melting	
Production phase	kg CO_{2eq}/kg
Atomization	1.64
Printing	13.2
Item and support removal	0.03
TOTAL (approx)	14.70

Table 16. Carbon footprint for selective laser melting

The amount of greenhouse gas production estimated to derive from the use of the three different techniques highlights how the values of emissions caused by selective laser melting were considerably lower than those caused by the other two techniques. It was also evident that, in all three techniques, the greater part of greenhouse gas emissions was ascribable to production phases that make a lengthy use of electrical power: coating annealing in classic and direct casting, the printing phase in selective laser melting. The fundamental impact on emission of plaster cast annealing in casting caused an upsurge in the production of greenhouse gas per kg of jewelry if the furnace was not completely full. In this case, in fact, emissions were no longer divided on the maximum number of cylinders that can be processed, but on a lesser quantity. The emission trend on varying the use of the furnace is shown in Figure 25, with the data given in the corresponding table at 100% efficiency.

In the SLM case, however, the emission varied as the printing speed changed, which, in turn, depended on the geometry of the items and the printing parameters used. Figure 25 shows the emission of the case studied in Table 16, corresponding to a printing speed of 14 g/h and the values corresponding to 7g/h and 25 g/h, which represent the speed range in which selective laser melting oscillates.

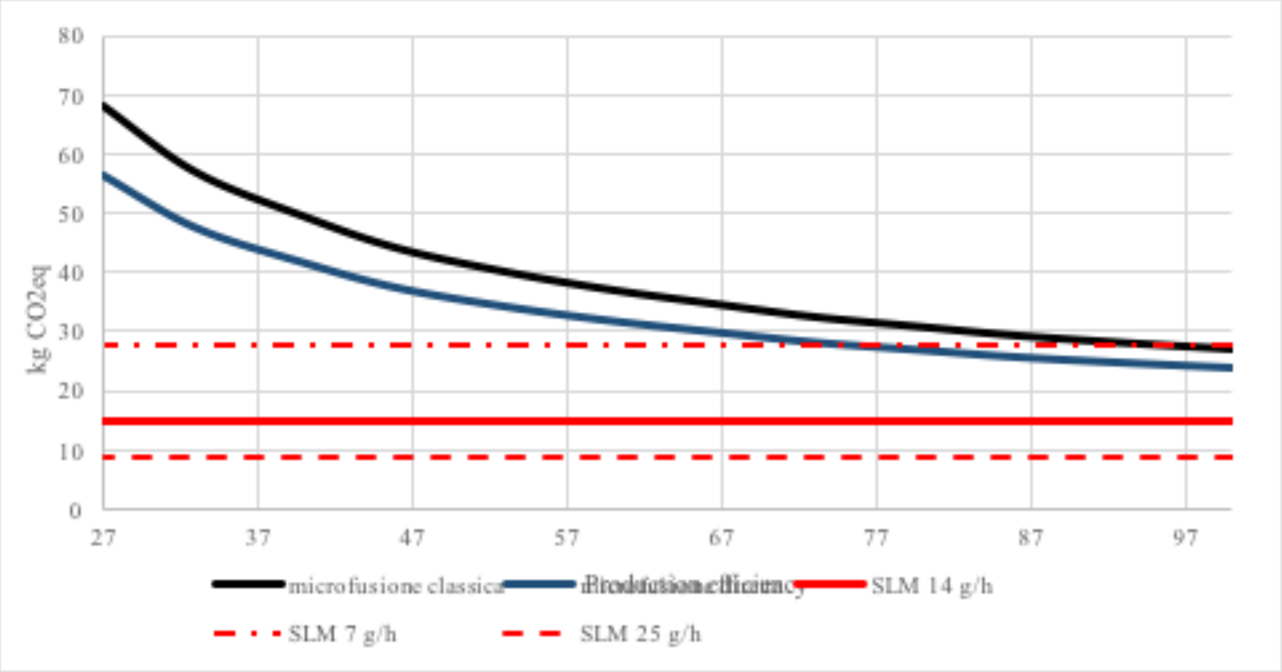


Figure 25. Trend of CO2 equivalent production on varying production efficiency

From the graphic comparison, it can immediately be noted how greenhouse gas emission is only lower with classic and direct casting when the printing speed is very low and castings are at high production efficiency In fact, generally, the CO2 equivalent produced in selective laser melting is clearly less, and can even be half that produced with classic and direct casting if these two techniques have a poor production efficiency, i.e. when the furnaces are under-used.
On the whole, it is therefore possible to conclude that the SLM technique is advantageous compared to casting in regard to environmental impact.

CONCLUSIONS

The study path and research carried out have allowed us to critically and objectively outline the advantages and disadvantages of the three main production techniques in the jewelry world: classic casting, direct casting and selective laser melting.
At this point the general performances analyzed are shown in a summarizing graph (Table 17). A score has been given to each characteristic, expressed as a given number of asterisks with a higher number of asterisks indicating the better result of the aspect in consideration. For example, a greater number of asterisks in definition indicates a better maximum resolution in the items produced, while a greater number of asterisks in production scrap indicates a lesser quantity of scrap material. The radar in Figure 24, showing the score attributed to each characteristic examined, helps to understand when using selective laser melting can truly be an advantage compared to classic and direct casting.

PRODUCTION TECHNIQUE	CLASSIC CASTING	DIRECT CASTING	SELECTIVE LASER MELTING
MATERIAL VERSATILITY	**	**	****
GEOMETRY FLEXIBILITY	**	***	***
SURFACE QUALITY	****	***	**
DEFINITION	****	*****	***
DEFECTOLOGY	**	***	*****
FINISHING LOSS	**	**	****
PRODUCTION CAPACITY	*****	***	*

MARKET PRICE	*****	***	**
SMALL QUANTITY LEAD TIME	*	***	*****
SERIES LEAD TIME	*****	****	*
ECOLOGY	**	**	***

Table 17.Comparison between the general performances of the three manufacturing techniques

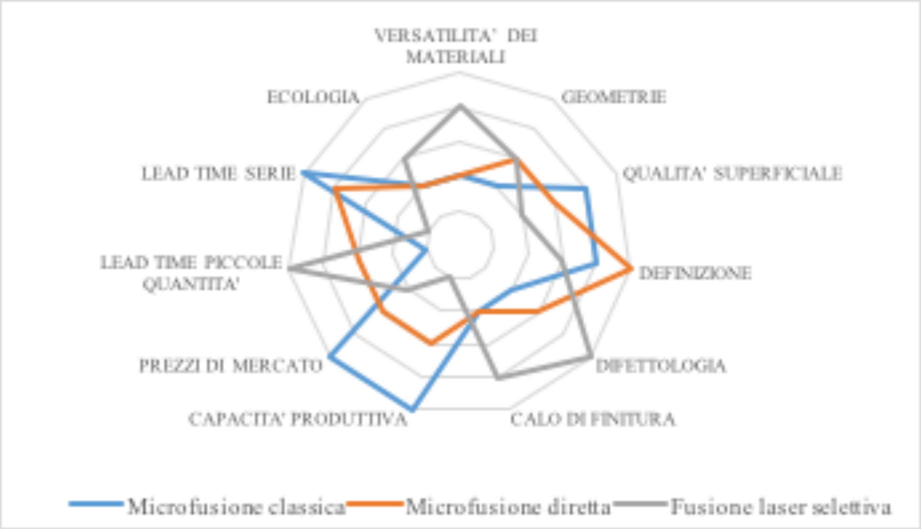


Figure 26. Comparison of the techniques

It is clear how the selective laser melting technique is generally a faster production technique than casting when a few items are to be produced, while, in the case of serial production, the greater production capacity of the casting technique, particularly classic casting, makes it more competitive in terms of time. Market prices are also decisively lower with this latter technique, while direct casting and laser printing have almost the same values. Due to its greater versatility, selective laser melting can therefore be advantageous, even in the case of serial production, when creating particularly complex geometries or in the case of using materials that are difficult or impossible to use in casting. Additionally, its higher production cost can be compensated by the possibility of emptying the items, taking, in this case, the final price of the jewelry to levels that can be lower compared to those produced with classic casting. The rougher aspect of the surfaces obtained with selective laser melting leads, however, to a greater finishing loss. In conclusion, at least from a general point of view, without going into the merits of a particular geometry or production requirement, selective laser melting is currently a technique that offers potentially greater versatility compared to the other more traditional techniques.

To conclude this comparison, the only thing left to say is that, at the moment, SLM is our vision of the future. Years ago, we began exploring the possible use of the selective laser melting technique in the field of jewelry, urged on by a dream and fascinated by an innovative technique. After years of research, tests and effective production, we are still convinced, now more than ever, of the potential of SLMTM as a jewelry manufacturing technique. However, it is important to use the right technique according to the type of production: not in all cases is production with SLMTM the most convenient. In fact, as we have said, there are cases in which classic casting is more convenient in terms of time and costs, as, for example, in the manufacturing of technically unproblematic jewelry series.

While, at the moment, the big companies still see the SLMTM technique as experimental and limited, in our vision of the future, the jewelry world will use it to the same extent as classic casting. In fact, the higher cost of the jewelry and a production time that is on average longer, can often be overcome by the greater geometric possibilities that selective laser melting offers compared to classic casting. As for direct casting, its versatility in geometric terms compared to the classic technique has already been surpassed at the moment by the potential of SLMTM. Moreover, selective laser melting has no negative consequences compared to direct casting that would make it disadvantageous in respect of the latter, therefore it is not utopian to think that it will gradually replace direct casting in the near future.

In conclusion, classic casting, with its heritage dating back to the dawn of time, and selective laser melting, the result of contemporary technology, could co-exist in the very near future, increasing the possibilities offered to jewelry producers in terms of economic savings and technical solutions.

BIBLIOGRAPHY

1. Investment casting of titanium alloys by induction melting. Dr. Ulrich E. Klotz, Tiziana Heiss. s.l. : Eddie Bell, Jessica Cast, Janet Haldeman, 2015. Santa Fè Symposium 2015. pp 169-179.

2. Optical properties of metallic films for vertical-cavity optoelectronic devices. A. D. Rakić, A. B. Djurišic, J. M. Elazar, and M. L. Majewski. 1998, Appl. Opt. 37, pp 5271- 5283.

3. Optimization of SLM Technology Main Parameters in the Production of Gold and Platinum Jewelry. Zito, D., et al. s.l. : Eddie Bell, 2014. The Santa Fè Symposium on jewelry manufacturing technology.

4. Additive Manufacturing of 18-karat Yellow-Gold Alloys. Klotz, U., Tiberto, D. e Held, F. s.l. : Eddie Bell, 2016. The Santa Fè Symposium on jewelry manufacturing technology. pp 255-272.

5. Latest developments in Selective Laser Melting production of gold jewellery. Zito, Damiano, et al. s.l. : Eddie Bell, 2012. Santa Fè Symposium. pp 537-562.

6. Casting Lightweight Hollow Jewelry Using 21st Century Technology. Bell, Eddie. s.l. : Eddie Bell, 2012. Santa Fè Symposium. pp 47 - 68.

7. “I Have Your Back”—How Innovative And Advanced Materials Cover Design And Advanced Materials Cover Design . Forno, I e Actis Grande, M. s.l. : Eddie Bell, 2012. Santa Fè Symposium. pp 203-225.

8. Innovative Mold Preparation And Cutting for Very Thin And High Precision Items. Schuster, Hubert. s.l. : Eddie Bell, 2009. Santa Fè Symposium. pp 359-377.

9. Going Thinner and Thinner: When Jewelry Needs Weight Watchers®! Actis Grande, M., et al. s.l. : Eddie Bell, 2013. Santa Fè Symposium. pp 1-16.

10. Correlation between porosity and processing parameters in TiAl6V4 produced by selective laser melting. Kasperovich, et al. 2016, Materials and Design, pp 160-170.

11. Stampa 3D Diretta in metallo: Un viaggio attraverso nuove opportunità e leghe innovative. Zito, D., et al. s.l. : Eddie Bell, 2017. Santa Fe Symposium on Jewelry Manufacturing Technology.

12. Optimization of the Main Selective Laser Melting Technology Parameters in the Production of Precious Metal Jewelry. Zito, D., et al. s.l. : Eddie Bell, 2013. The Santa Fè symposium on Jewelry Manufacturing Technology. pp 1-20.

13. Definition and Solidity of Platinum Jewelry Produced Using Selective Laser Melting (SLM™) Technology. Zito, Damiano, et al. s.l. : Eddie Bell, 2015. The Santa Fè Symposium on jewelry manufacturing technology. pp 455-492.

14. Istituto Superiore per la Protezione e la difesa Ambientale . Fattori di Emissione Atmosferica di CO2 e Sviluppo delle Fonti rinnovabili nel settore elettrico. s.l. : ISPRA - publishing sector, 2015.

16. German, Randall. Powder Metallurgy and particulate materials processing. Princeton : MPIF, 2005.

17. Definition and Solidity of Platinum Jewelry Produced Using Selective Laser Melting (SLM™) Technology. Zito, Damiano, et al. s.l. : Bell, Eddie; Cast, Jessica; Haldeman, Janet, 2015. The Santa Fè Symposium on jewelry manufacturing technology. pp 455-492.