POTENTIAL AND INNOVATION OF SELECTIVE LASER MELTING TECHNIQUE IN PLATINUM JEWELRY PRODUCTION

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INTRODUCTION

In the paper[1] presented at the 2017 Santa Fe Symposium®, we compared, in a general way, the casting process with Selective Laser Melting (SLM™) to understand when this latter technique is, in fact, advantageous over casting, both traditional and direct from printed patterns. Among the productive cases in which selective laser melting turns out to be superior are 1) the production of small quantities, 2) the production of objects that are hollow or have complex geometries, and 3) the usage of difficult or impossible materials for casting.

The production of platinum jewelry could be among these cases since casting this material is by far more complicated than casting silver or gold alloys.[2] Furthermore, in spite of the growing interest in platinum in the last 20 years, the market for platinum jewelry is understandably smaller than for gold and silver jewelry. For this reason, casting machines dedicated to platinum jewelry are usually used well under their full productive capacity.

In order to analyze when and if the SLM™ technique can complete with casting when producing platinum jewelry, we carried out a real-life production comparison between the techniques. This was effected thanks to a collaboration between Progold3D®, reference entity for selective laser melting, and Stilnovo S.r.l from San Salvatore Monferrato (jewelry district of Valenza, Italy), OEM jewelry producer and reference entity for platinum casting.

The market segment selected to compare the two techniques was that of wedding and engagement rings, since it is the most representative segment in both Europe and the USA at this time. The idea of eternity (associated with platinum due to its high resistance to alterations over time) makes this element particularly sought after for nuptial rings. This was demonstrated through the USA 2016 market data,[3] which showed that even though the platinum jewelry market fell by 10% over the preceding year, American acquisition of platinum wedding bands increased by 5%, thus making this segment more predominant than in the past.

WHAT CHANGES WITH RESPECT TO GOLD JEWELRY PRODUCTION?

Platinum jewelry production using traditional methods, particularly casting, presents additional difficulties compared to gold jewelry production. However, platinum jewelry production using SLM™ does not show exceptional complications when compared to the production of gold alloys. This fact makes this technique extremely interesting for the production of objects made with platinum. Generally, at least for the metals that are used in jewelry, the more complicated it is to cast, the easier it is to produce using direct 3D printing.

The most obvious production issue during casting stems from the differences between the thermo-physical properties of platinum and gold alloys. First of all, the higher liquidus temperature of platinum alloys requires the use of different refractory materials for the flasks—materials that are capable of resisting higher temperatures. Instead of using traditional calcium sulfate and cristobalite investments, it is necessary to use materials that are more temperature resistant and in which silica is usually coupled to phosphate bonding agents, rendering the preparation phase more time-consuming and arduous.[4] Imperfect mixing, possibly due to an inappropriate water-powder ratio or to inadequate mixing times, makes the refractory properties vary in a more dramatic way than they do for their equivalent in gold casting. These materials are, in fact, far more sensitive to stocking and aging conditions than traditional investments, thus causing hard-to-manage variations in both surface quality and mechanical properties.[5]

Even when using the appropriate materials, the flasks' strength is critical if they are heated above 900°C (1652°F).[6] This limiting temperature leads to a higher thermal difference between flask and molten metal for platinum casting, which translates into a faster heat loss by the poured metal. This effect, coupled with the higher viscosity and surface tension of platinum alloys, makes the complete filling of the patterns more difficult, especially in the thinnest zones. Using a centrifugal casting system helps reduce this incomplete filling problem.[6] A drawback to increasing the centrifugal force is the possibility of the investment breaking apart and becoming an inclusion in the cast metal. The combination of these hindrances limits the quantity of metal that can be used for the production of each tree, implying a lower productive capacity with platinum than with gold and silver trees. The form filling difficulties and the higher shrinkage in the transition from liquid to solid also means that a more consistent feeding system is needed and that the ratio between scraps and produced objects is unfavorable. A higher quantity of scraps implies an elevated production cost, which is further increased by the refining process since it is more costly to refine platinum than gold due to the difficulties during both melting and assaying. The addition of all these disadvantages not only renders the casting of platinum jewelry more susceptible to variation in results but also requires a more experienced operator for its production.

By considering the SLM™ process instead, no particular issues for platinum alloys can be found that gold alloys do not also present. Actually, the fundamental properties for the metal–laser interaction, especially reflectivity and thermal conductibility, are more favorable with platinum alloys than with silver or gold alloys. This entails a lower necessary energy for the laser melting and eliminates the necessity of adding elements to the alloy that favor the absorption of the laser radiation.

QUALITATIVE COMPARISON

The qualitative comparison between platinum jewelry produced using SLM™ and casting was done by producing some ring models belonging to the BRIDAL collection of the company Stilnovo. This collection is the one that reflects the concept of eternity that is commonly associated with platinum jewelry because it is made up of rings presenting the Multisize Ring solution (Patent pending 102017000104245 granted on September 18, 2017).

The multisize patent is a system that views a ring in a whole new way as an object that can easily transform its own diameter and thus remain perfectly wearable. Changing the size of a ring has always been somewhat of a problem for both jeweler and the final user. Since a jewel is an object that lasts over time and often passes from mother to daughter, it becomes highly probable that a change in measurement is required, particularly for a different finger size or change of ownership.
Ring sizing is quite simple for engagement rings where stones are set only at the top and the ring shank is solid metal underneath. In such cases, the ring can be enlarged by cutting the bottom of the shank and inserting a piece of matching metal or made smaller by removing a section. However, sizing becomes more complex for an eternity ring where stones are set all the way around the ring. Any change to the curvature of an eternity ring after the stones are set will risk making the stones loose.

With the Multisize Ring solution, the inside of the ring shank is a channel (part A in Figure 1), into which a metal spring that varies in thickness can be inserted to change the finger size of the ring (part B in Figure 1). The external part of the ring is produced in platinum (although other metals can be used) while the internal sizing spring,which is interchangeable to all ring styles, is produced in titanium. By varing the thickness of the spring, four finger sizes can be accommodated.

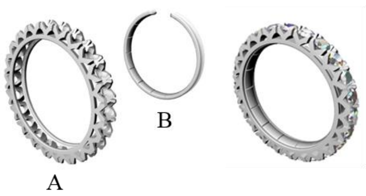

Figure 1 *Body and interchangeable spring for the ETERNAL model*

A simple key, a hook made in titanium, having the shape of a treble clef (Figure 2), aids in the removal of the internal spring when this has to be changed.

Figure 2 *Key for changing the spring*

Figure 3 shows the sequence for using the key to change the internal spring. There is a small hole in the internal spring into which the hook on the end of the key can be inserted. Then the spring is pulled toward the inside of the ring and once clear of the channel it is pulled outward until it is free.

Figure 3 *Sequence for removing the interchangeable spring for the Trilogy model*

For the comparison between casting and direct metal printing, 10 ring models of the Bridal collection were selected, among which were wedding bands, solitaires and trilogies. The body of these models can be observed from *Figure 4* to *Figure 13*. The production and the characteristics of the internal interchangeable springs were not taken into consideration in this study since they were not produced using platinum alloys but produced mainly in titanium due to the mechanical properties required to allow a continuous insertion and removal of the springs from the body without deforming.

Figure 4 *Body of band model 1*

Figure 5 *Body of band model 2*

Figure 6 *Body of solitaire model 4*

Figure 7 *Body of solitaire model 5*

Figure 8 *Body of solitaire model 7*

Figure 9 *Body of solitaire model 8*

Figure 10 *Body of solitaire model 15*

Figure 11 *Body of solitaire model 16*

Figure 12 *Body of trilogy model 1*

Figure 13 *Body of trilogy model 2*

A ring model called ETERNAL (Figure 14), with stones set 360° around the circumference, was initially chosen for the comparison but it was immediately discarded due to the difficulties in removing the supports required for the production of pieces using SLM™ .

Figure 14 *Body of band ETERNAL model*

For each production technique under observation, six rings per model were produced, two of which were destined to be used in destructive analyses. The exception are the two band models, of which only three bands for each gender were produced. The total amount of rings used for this study was 120 pieces, 40 of which were sacrificed for destructive analysis. The summary of all the pieces produced can be seen in **Error! Reference source not found.**.

Table 1 *List of the pieces produced for each model and production technique*

Model	Cast Pieces	Printed Pieces SLM™	Total
Solitaire 4	6	6	12
Solitaire 5	6	6	12
Solitaire 7	6	6	12
Solitaire 8	6	6	12
Solitaire 15	6	6	12
Solitaire 16	6	6	12
Trilogy 1	6	6	12
Trilogy 2	6	6	12
Band 1	3M+3F	3M+3F	12
Band 4	3M+3F	3M+3F	12
	Total		120

In order to render the comparison more similar to a real production test, the production of the rings was divided between two producers: Stilnovo for casting and Progold3D® for selective laser melting. Each producer is a specialist in one of the two techniques that is being considered in this case study and is thus capable of optimizing the process to obtain the best quality possible.

With the objective of evaluating the qualitative differences given exclusively by the production process and not by the differences of the composition, a 95PtGaInCu alloy, which is suitable for both SLM™ and casting, was chosen. The use of the same alloy composition in both cases is possible without giving advantage to one technique over the other thanks to the relative easiness with which platinum can be melted through laser interaction.

Regarding casting, waxes were made using a 3D system printer, Project MJP 2500W, using the brand VisiJet® M2 Cast. Flasks were prepared using Pro-HT Platinum Gold Star® investment powder, maintaining a water/powder ratio of 33:100. The burnout cycle is shown in Figure 15. Flask temperature during casting was 850°C (1562°F). Preparation of the flasks and burnout cycle was grouped together as much as possible, trying to achieve a compromise between production times and need to recuperate the scraps.

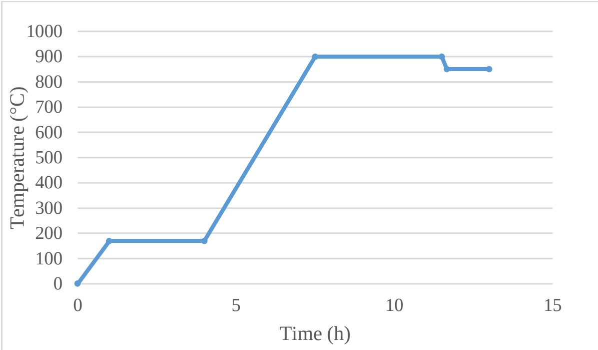

Figure 15 *Burnout cycle*

For the melting process and filling of the flasks, a Yasui VCC centrifugal casting machine was used, setting a temperature that was 250°C (450°F) higher than the liquidus of the alloy. After quenching the flasks, investment residuals were removed by immersing the pieces in hydrofluoric acid at ambient temperature. A final sandblasting treatment was executed to completely remove investment residues.

Regarding selective laser melting, jewels were produced using a ReaLizer® SLM50 printer equipped with a 100W fiber laser, collimated in a 10 µm diameter spot. A 70 mm circular construction platform was used. The layer thickness selected for the printing process was 20 µm, choosing print resolution over production speed to satify the needs of a high-quality market segment.

The printer was fed with 95PtGaInCu powder, obtained through gas atomization of the alloy and sieving to remove the coarsest particles. The shape of the powder particles was observed using a scanning electron microscope (SEM) and the dimensional distribution was determined through a laser granulometer (Malvern, Hydro 2000S). After printing, a shot peening of the rings followed to eliminate some of the incidental powder particles remaining on the surface, which were responsible for the elevated roughness of the pieces.

In both cases, casting and direct printing, all the rings produced were annealed to solutionize the alloy and eliminate internal residual stresses. This was done by inserting the samples in an oven heated to 1150°C (2102°F) and fast quenching in water. In the case of the wedding bands, the pieces were immediately age hardened in an oven set to 650°C (1202°) for one hour, followed by a slow cool down to room temperature.

Independent of the technique employed for the production of each ring, the following qualitative parameters were evaluated:

- Surface aspect "as cast" or "as printed" and impact of feeders or residual supports
- Identification of macroscopic defects that could lead to non-conformity
- Measurement of the ring's internal diameter, discrepancy with nominal value and deviation between rings of the same model

The two sacrificial samples also underwent the following:

- Measurement of the surface roughness, both "as cast" or "as printed," and after sandblasting or shot peening.
- Evaluation of the internal quality by cross-sectioning and lapping

All jewels produced that were not destined for destructive analyses (40 cast rings and 40 printed rings, divided among 10 models) were polished and eventually set at Stilnovo for the final evaluation of the jewelry quality. The QC department of Stilnovo, not informed about the technique used to produce the rings under analysis, gave the qualitative judjment of the final piece, applying the same standards that are usually employed for high-end fine jewelry QC.

At the same time, the following fundamental data regarding economic and technological aspects for casting and direct metal printing were registered:

- Production time
- Production scraps
- Operators' opinions during polishing
- Operators' opinions during setting

To properly collect all data regarding finishing operations, an evaluation data sheet was filled out and submitted by each operator for each ring.

EVALUATION OF THE PHYSICAL, MECHANICAL AND TECHNOLOGICAL CHARACTERISTICS

Surface Quality

The first comparison between rings made by casting and by SLM™ regards the appearance of the surfaces at the rough state and after sandblasting or shot peening. This includes the evaluation of the impact that additional elements, such as feeders in the case of casting or supports in the case of printing, have on the surface. The magnitude of surface imperfections have a direct effect on the necessity of reconstructing the surfaces and, in terms of economics, are directly proportional to the production of scraps and extended processing time.

Figures 16–25 compare the feeders and supports of the 10 models that were chosen for production.

Figure 16 *Feeders and supports used for the production of band model 1*

Figure 17 *Feeders and supports for band model 2*

Figure 18 *Feeders and supports used for solitaire model 4*

Figure 19 *Feeders and supports for solitaire model 5*

Figure 20 *Feeders and supports for solitaire model 7*

Figure 21 *Feeders and supports for solitaire model 8*

Figure 22 *Feeders and supports for solitaire model 15*

Figure 23 *Feeders and supports for solitaire model 16*

Figure 24 *Feeders and supports for trilogy model 1*

Figure 25 *Feeders and supports for trilogy model 2*

Comparing the feed sprues for casting and the supports for SLM™-printed parts shows the two production techniques have a completely different effect on surface geometry. In casting, where the additional elements are massive, the geometry of the zones where the metal is fed directly is lost, while in SLM™ the supports, which are constructed ~~in~~ as a mesh, generally allow the underlying geometries to be seen. Examples of support and feeder residuals can be seen in Figure 26 and Figure 27.

The SLM™ supports are generally-spread over a greater surface area of the piece but not if the effective contact area is considered. The areas where the mesh is attached to the surface and damages it are generally less than the feed sprue attachment areas in casting. There are some pieces, such as the Eternal model, that can't be produced economically using selective laser melting even though the geometry is compatible because of the massive presence of support residuals.

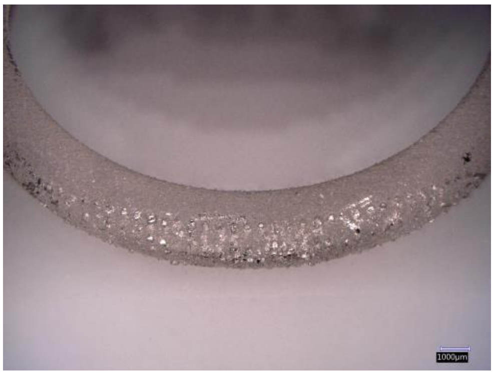

Figure 26 *SLM™ support residuals on a ring's surface*

Figure 27 *Feeder residual on a ring's surface*

For the Solitaire 4 and Trilogy 1 models, a good compromise was obtained using a growth orientation that minimized the presence of slope angles requiring further supports (
Figure ***28*** and 29**)**. A good usage of these parameters allows the creation of supports that are more easily removed even if a higher dexterity is required during removal.

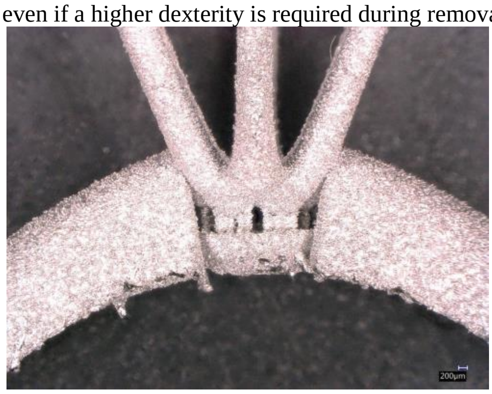

Figure 28 *Internal supports of solitaire model 4*

Figure 29 *Internal supports of trilogy model 2*

Regarding the overall appearance of the surfaces, the cast rings seem generally less rough both before (*Figure 30* and 31) and after surface treatment (*Figure* 32 and 33).

Figure 30 *Rough band model 4 produced using casting*

Figure 31 *Rough band model 4 produced using SLM™*

Figure 32 *Cast band model 4 after sandblasting*

Figure 33 *SLM™-produced band model l4 after shot peening*

Roughness

For a quantitative evaluation of surface differences, some roughness measurements were done using a profilometer Taylor Hobson FTS INSTRA 0.2. The value considered for the comparison was the profile total roughness (R_t), that corresponds to the difference between the highest and the lowest point of the surface and signifies the thickness layer of precious metal that has to be removed during polishing to obtain an aesthetically pleasing surface. The values were registered for as-cast and as-printed pieces, and after sandblasting or shot peening.

Shot peening is used to smooth the surface of SLM™ parts and sandblasting is used to remove investment residues from Pt castings. The roughness values represent the quantity of material that would have to be removed to obtain a polished surface.

Measurements were done on more than one area of the piece, corresponding to planes with different orientation with respect to the pieces' growth direction in SLM™ and the wax pattern growth in casting. For measurement, points free of evident surface defects were selected to get the average value of R_t without considering macroscopic surface irregularities.

For the wedding bands, the growth orientation chosen for 3D printing of the waxes for casting and for the metal in SLM™ were the same and are represented in **Error! Reference source not found.**. Measurements were done in direction 1 (plane parallel to the z axis, the direction of growth), in direction 2 (plane parallel to the growth, direction perpendicular to z) and direction 3 (plane perpendicular to the growth, direction perpendicular to z).

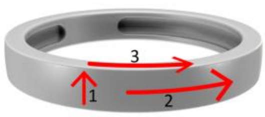

Figure 30 *Roughness measurement directions for bands*

The solitaire and the trilogy casting patterns were printed horizontally, while the SLM™ parts were produced standing upright because of the different usable supports. In this case, measurement directions were named according to the growth orientation as reported in Figure 31 for SLM™ rings and in *Figure 32* for cast rings. Direction 4 corresponds to a plane perpendicular to the growth direction while 5 corresponds to a measurement along z.

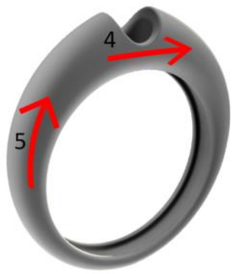

Figure 31 *Roughness measurement directions for SLM™ solitaires and trilogies*

Figure 32 *Roughness measurement direction for cast solitaires and trilogies*

The average values determined for the rough state of the pieces (as-cast and as-printed) in each direction are reported in Table 2 with the corresponding standard deviations. The same values are reported in Table 3 but after sandblasting and shot peening. Results are summarized in the graph in Figure 37.

Table 2 *Roughness "as cast" and "as print"*

Casting			SLM™		
Direction	**R_t (µm)**	**Dev std**	**Direction**	**R_t (µm)**	**Dev std**
1	46	7	1	55	16
2	32	10	2	40	13
3	17	10	3	63	19
4	34	4	4	49	12
5	37	8	5	54	12

__Table 3__ Roughness after sandblasting (cast pieces) or shot peening (SLM™ pieces)

Casting			**SLM™**		
Direction	**R_t (μm)**	**Dev std**	**Direction**	**R_t (μm)**	**Dev std**
1	24	5	1	36	7
2	15	7	2	22	10
3	12	3	3	35	10
4	12	3	4	27	12
5	21	8	5	35	12

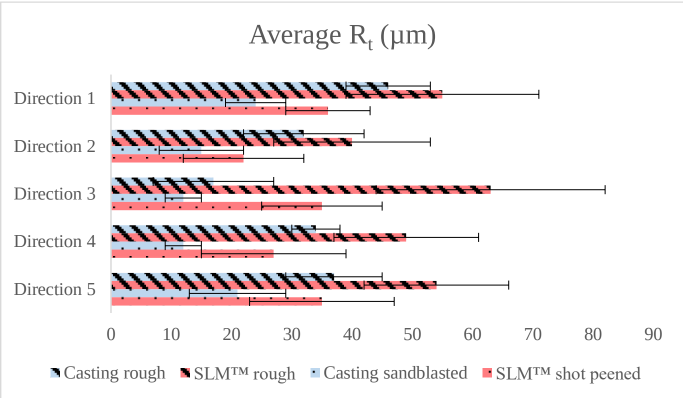

Figure 33 *Average roughness for SLM™ and cast pieces*

As noted from the observations on the rough surfaces, the values of roughness for SLM™ - printed pieces are decisively higher than those of the cast pieces. This result is not surprising since this is, in fact, one of the weakest points of the SLM™ technique. Furthermore, in SLM™ the registered roughness is on average higher than the roughness determined for gold alloys produced using the same technique. This data is in line with the values reported in the study conducted by Progold in 2015,[7] in which it was observed how the presence of more powder particles partially melted on the surface of the pieces in platinum alloys with respect to gold alloys leads to a higher ~~superficial~~ surface roughness (Figure 38).

The highest "as-printed" roughness registered for SLM™ in direction 3 can be explained through the surface irregularity coming from the fusion lines that are higher in the middle than on the borders (Figure 39). On the printed waxes this surface behavior is a lot less evident (

Figure *36* 40) to the point that the roughness caused by this effect along direction 3 gives smaller values of roughness than those generated by the division of the layers along z, which is the main culprit of the roughness in the other directions.

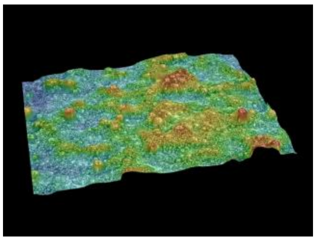

Figure 34 *Surface roughness of a rough SLM™ band , 300X*

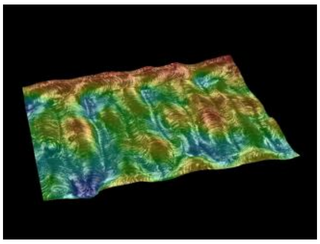

Figure 35 *Surface roughness along a horizontal wall of a rough SLM™ band, 300X. The parallel traces left by the laser scans are visible.*

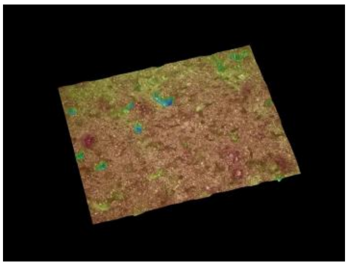

Figure 36 *Surface-roughness along a horizontal wall of rough cast band, 300X*

The higher standard deviation for SLM™ reflects the high roughness variability between different zone on the same piece. These differences are due mainly to the different orientations of the measured surfaces with respect to the movement done by the wiper during the recoating of the platform,[7] which translates into diverse adhesion between the powder particles and the surface. In comparison, roughness in cast pieces is more constant on a single model as well as across the range of different models. However, the effect of surface treatments, either shot peening on SLM™ or sandblasting on castings, reduces surface roughness by about half.

The lower surface roughness that was measured overall in casting implies that less material will have to be removed by the jeweler during contour sanding to acheave a polished surface.

This is only true, however, if there are no zones presenting missing material such as cavities. In these cases, which were commonly observed during this study for the rings that were cast, the material loss and the working times were considerably higher.

Defects

Casting

Cast jewels show more surface defects than jewels produced through SLM™ , even after having optimized the casting parameters. The most common defects that were observed were surface irregularities, such as excess fins or voids.

In the first case (*Figure 37*), the cause of excess fins is the partial rupture of the investment, leaving behind fissures that are then filled with metal. This type of defect is generally very easy to fix since removal of the excess material does not require a lot of time.

Figure 37 *Material excess on the side of the cast ring (fin defect)*

In some pieces, however, like in trilogy model 1, the presence of details that are separated by small spaces renders fin defects more critical. This is what happened to the casting shown in *Figure 38*, where-the rupture of the investment led to fins completely closing areas that should be open. The variability in strength of phosphate-bonded investment, its vulnerability to pressure shock, and the high temperatures during casting are the most probable causes for this type of defect.

Figure 38 *Example of finning caused by investment rupture*

Defects called investment inclusions result when small particles of the investment mold detach and fall into the pattern cavity. The metal fills around these investment particles, forming irregularities like emerging cavities (

Figure 39 and

Figure 40**), or surface depressions when the detached particles float on the metal (**
Figure 41).

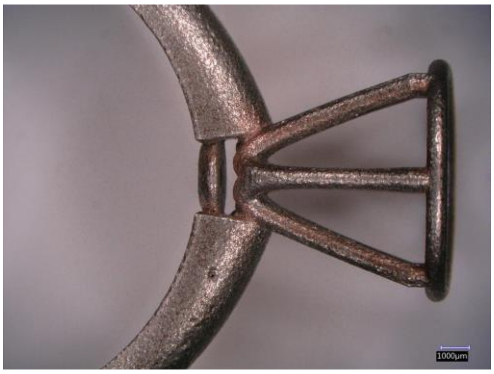

Figure 39 *Emerging cavity on the surface of a solitaire model 4, probably caused by an investment detachment that was trapped in the molten metal*

Figure 40 *Close-up of the defect shown in Figure* ***39***

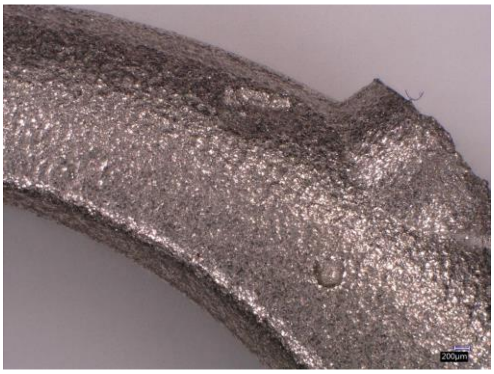

Figure 41 *Depressions probably caused by detached fragments of investment floating on the surface of the molten metal*

The high temperature of the metal, which sparks reactions with the investment, is the probable cause of the irregular surfaces and of the porosities observed in some of the zones of the cast rings, like the ones presented in

Figure 42 and 47, where roughness is noticeably higher than the average of the surrounding zones.

Figure 42 *Irregular surface on cast solitaire model 7*

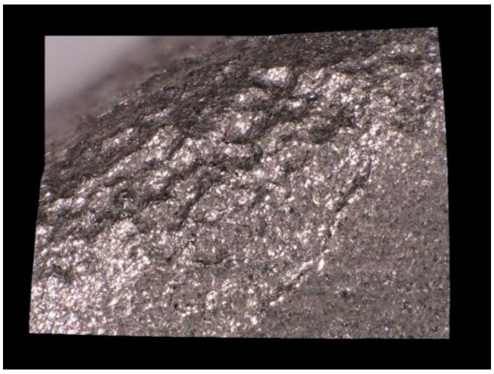

Figure 43 *Detail of the surface of Figure* ***42***

In other jewels, the surface defects seem to derive from a combination of investment detachments and reaction of the refractory material (**Error! Reference source not found.**).

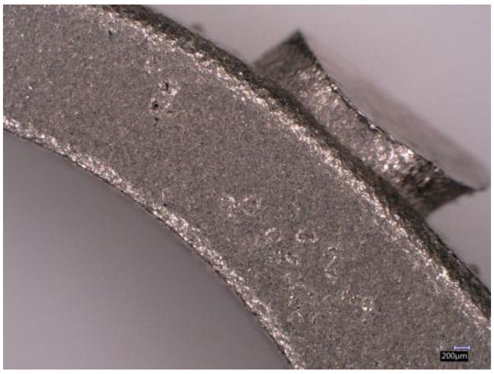

Figure 44 *Surface porosity on cast solitaire model 8*

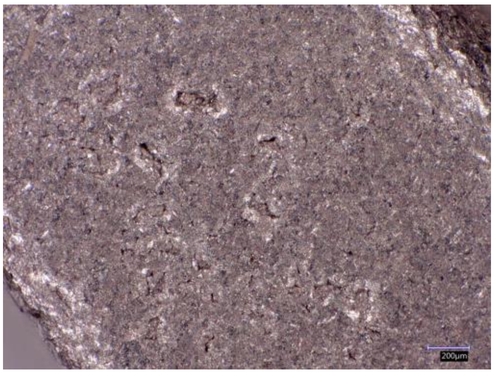

Figure 45 *Detail of the zone in Figure* ***44***

The defects presented in

Figure 39–49 are more damaging than the previous fin defects since there is a lack of material instead of an excess of it. This in fact makes the operator remove more material in order to achieve a more regular surface or to carry out repairs to fill deep hollows. This means a higher scrap loss and longer working times.

Besides the defects explained through the metal–investment reaction, some other defects ~~deriving~~ originating from other production phases were observed. Cast solitaire model 8 became slightly oval in shape (Figure 50), possibly due to tension in the waxes or to problems during the pouring of the liquid investment. Even though the jewel is deformed, only a small correction by the jeweler is required to return it to its original shape, making this just a minor problem.

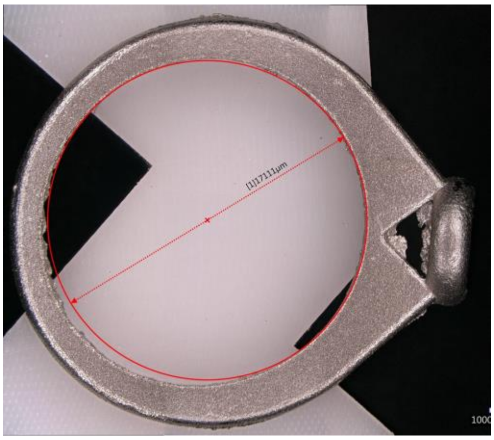

Figure 46 *Cast solitaire model 8 with evident ovalization*

Another defect observed was bent prongs in the models with tall settings. This is especially so for the solitaire model 4. This problem (Figure 51), probably due to a bending of the waxes during flask preparation, was solved by adding a terminal ring that helped prevent an eventual movement of the prongs (Figure 52).

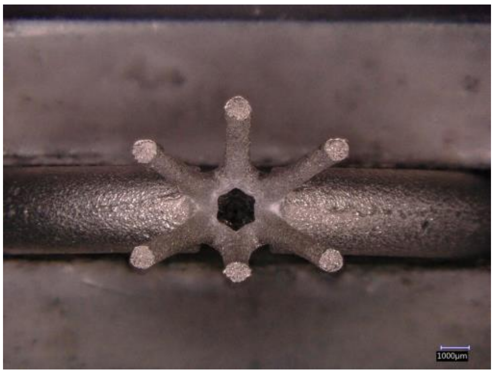

Figure 47 *Deformation of the prongs in cast solitaire model 4*

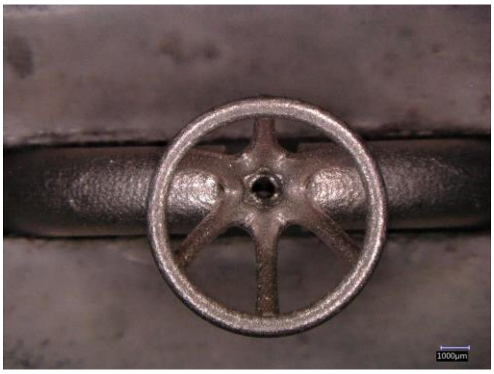

Figure 48 *Added ring to stabilize the position of the prongs in the cast solitaire model 4*

The cracked shank shown in Figure 53 was attributed to mechanical stresses that developed during quenching. In this case the ring is obviously non-conforming and must be scrapped.

Figure 49 *Cracked ring shank*

In order to further investigate the causes of the cracked shank, it was sectioned horizontally and analyzed using a scanning electron microscope. Inside the shank, in the area corresponding to the rupture, a cavity was observed that was left, in all probability, by an investment inclusion given the results of an EDS analysis that evidenced the presence of silica in that section.

The cavity, which extended across the two halves of the band after sectioning (Figures 54 and 55), reduced the effective section of the ring and consequently drastically reduced its mechanical resistance. The stress generated by shrinkage during quenching was greater than the ultimate tensile strength, allowing the ring shank to break.

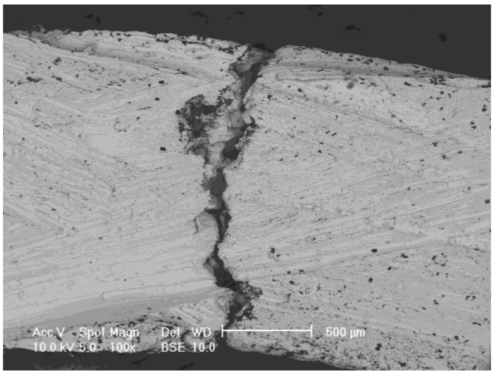

Figure 50 *Internal cavity in a cast ring shank, corresponding to the fractured section.*

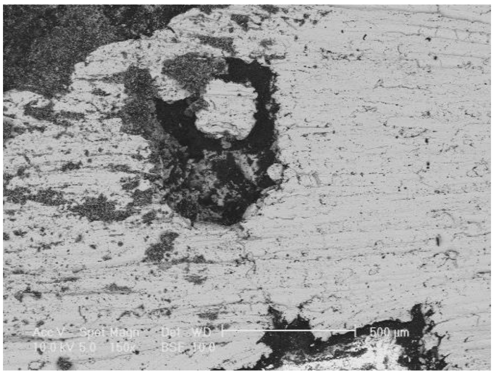

Figure 51 *Extension of the cavity on the other half of the sectioned ring shank*

SLM™

The macroscopic defects observed on jewels produced by SLM™ were considerably fewer than those found in cast pieces. Even though the surfaces had a higher roughness, only in one single ring was a real irregular zone verified as a swelling in a zone of the ring (Figure and 57). This type of defect appears in SLM™ pieces when the fusion of the powder is non-optimal, i.e., incompletely melted particles remain on the working surface and subsequently disturb the newly added printed layers. For this specific case, since the defect was found only in one small area of the upper part of the piece, the incomplete fusion was probably the consequence of a variation of the average particle size in the growth area. This could be, for example, caused by an accumulation of partially molten particles inside the powder that is distributed by the wipers during printing.

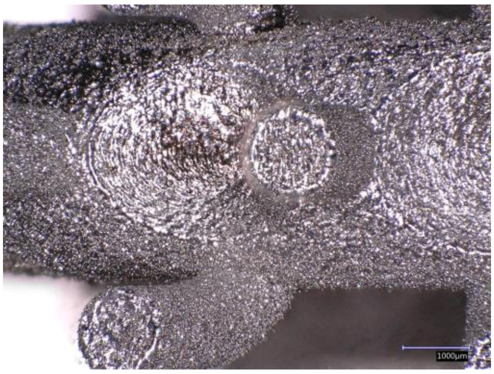

Figure 52 *Surface swelling of an SLM™ trilogy model*

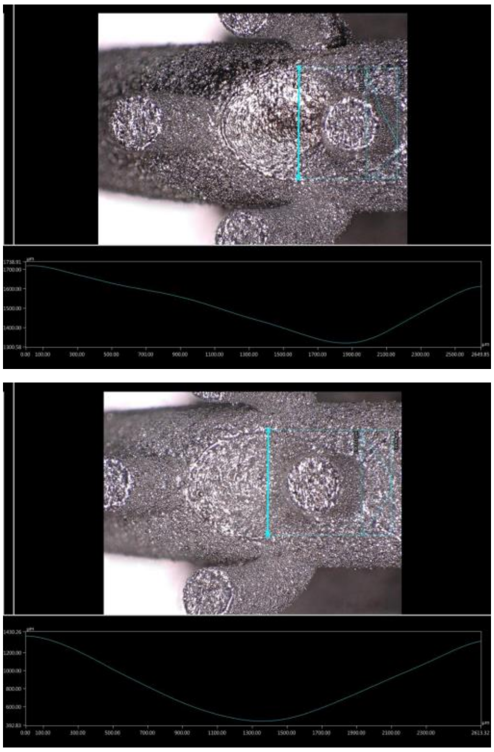

Figure 53 *Defect on a trilogy ring surface (upper image) compared to the surface of a standard one (lower image)*

Being an excess of material and not a lack of it, correcting a defect of this type is not a serious problem, provided a porous area, also caused by the incomplete fusion, is not hidden under the swelled surface

Dimensional Coherency

An analysis of dimentional compliance and of the deviations found between different rings of the same model was done on all the rings by measuring the internal diameter, and then comparing them to the design value. To achieve better precision, each diameter was measured in two distinct ways: first using a caliper (Mitutoyo) and averaging three values measured in different points of the circumference, followed by image analysis using a Keyence digital microscope that was especially calibrated to maximize the accuracy of the measurement (Figure 58).

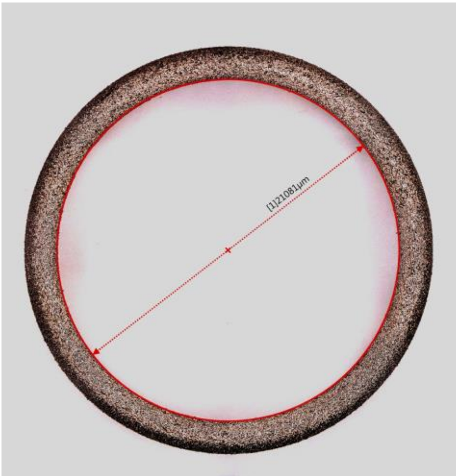

Figure 54 *Example of digital measurement*

Error! Reference source not found. shows all data regarding the internal diameter of the rings. For the mean values calculated for casting, the ovalized ring shown in Figure 50 was not taken into consideration due to the difficulty in measuring the exact internal diameter.

Table 4 *Deviation between nominal value and the measured value for rings produced with each technique*

Internal Diameter (mm)					
Model	**nominal**	**casting**	**Std dev casting**	**SLM™**	**Std dev SLM™**
Solitaire 4	17.66	17.43	± 0.04	17.57	± 0.02
Solitaire 5	17.66	17.52	± 0.03	17.55	± 0.03

Solitaire 7	17.67	17.48	± 0.04	17.56	± 0.02
Solitaire 8	17.65	17.46	± 0.02	17.61	± 0.03
Solitaire 15	17.66	17.46	± 0.01	17.58	± 0.02
Solitaire 16	17.65	17.47	± 0.03	17.55	± 0.02
Trilogy 1	17.59	17.42	± 0.03	17.51	± 0.02
Trilogy 2	17.72	17.53	± 0.01	17.65	± 0.02
Band 1M	21.10	20.96	± 0.02	21.11	± 0.01
Band 1F	17.65	17.53	± 0.05	17.61	± 0.01
Band 4M	21.10	20.96	± 0.01	21.08	± 0.03
Band 4 F	17.65	17.53	± 0.03	17.65	± 0.01

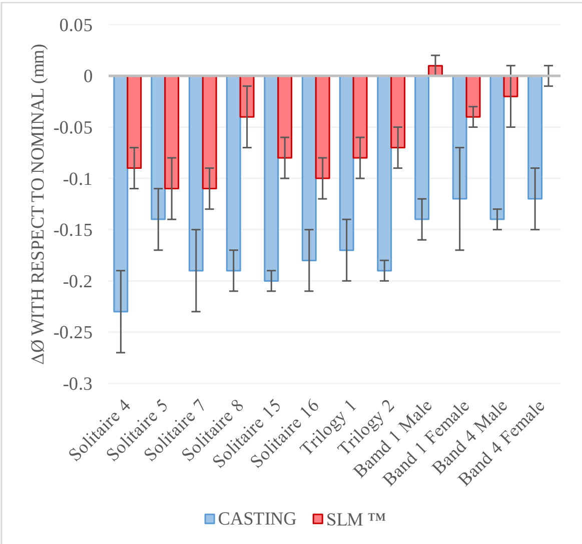

***Figure 59** Variation with respect to the nominal measure of the internal diameter with standard deviation*

From the data obtained (Figure 59), it can be seen that the difference between the real and the nominal diameter is always smaller for the SLM™ rings than for the cast rings. The cause for the variation of the internal diameter is obviously different for the two techniques. With SLM™ it is caused by an imperfect correction of the width of each single laser trail, while in casting it is due to the shrinkage of the investment during the firing, the shrinkage of the metal when transitioning from liquid to solid and the contraction of the piece while cooling down to ambient temperature.

In the case of SLM™, the use of platinum instead of gold does not represent a variable that can influence ~~on~~ the dimensional variation. In casting, however, the higher temperature and a more marked shrinkage during solidification can have greater influence on dimentional variation for platinum rings than ~~on~~ gold rings. Also, the repeatability of rings of the same model is generally better for SLM™, with maximum standard deviations of ± 0.03 mm versus the more than ±0.04 mm determined in some cast models. Given the larger variation that was seen in casting, it is anticipated that eventual correction of the internal dimensions, i.e., by modifying the design, will turn out to be less effective.

Internal Porosity

To analyze the pieces for internal porosity, computerized X-ray tomography was initially considered since it has the advantage of being nondestructive and can scan the whole volume of the jewel at once. The results obtained, however, were not satisfactory in terms of image resolution due to the high density of platinum, which causes such a high absorption of the beam as to render the analysis imprecise due to the thickness of the rings.

As an alternative to tomography, two rings of each model and production technique were sectioned and analyzed. In order to make the evaluation as complete and as representative of the whole volume as possible, different zones of the rings were sectioned. In particular, one sacrificial ring was sectioned through plane A shown in Figure 60, while the other was sectioned alongside plane B (Figure 61), perpendicular to the first one, in four different areas of the sample. After embedding the sections in resin and lapping, they were photographed with 50X magnification for digital analysis of the porosity using internal software of the Keyence microscope that was used to obtain the images.

Figure 55 *Plane of section A*

Figure 56 *Plane of section B*

The sections through plane A, that present larger surfaces than those alongside plane B, are shown in
Figure –81. The values of the total percentage porosity that was determined by considering both sections A and B of each ring and weighted by the total surface area of each analyzed section are reported in Table 5.

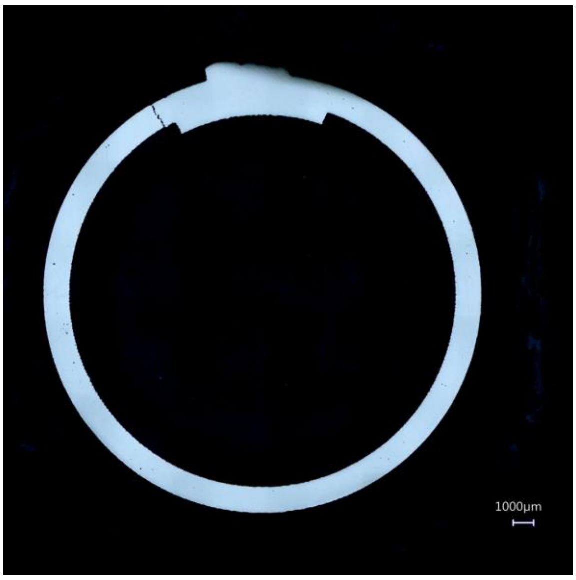

Figure 57 *Cast band model 1*

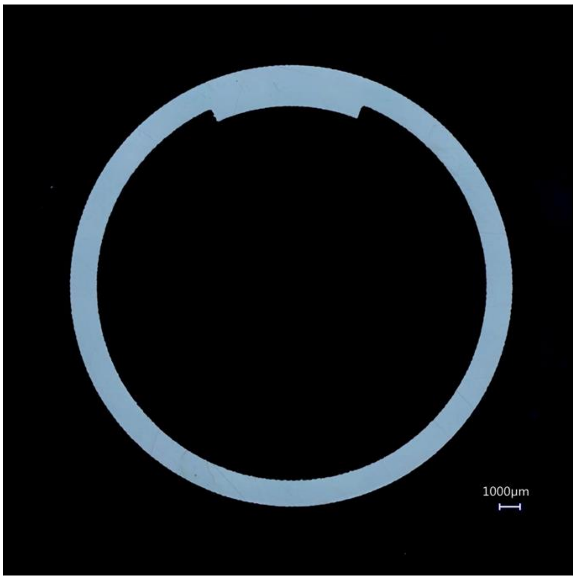

Figure 58 *SLM™ band model 4*

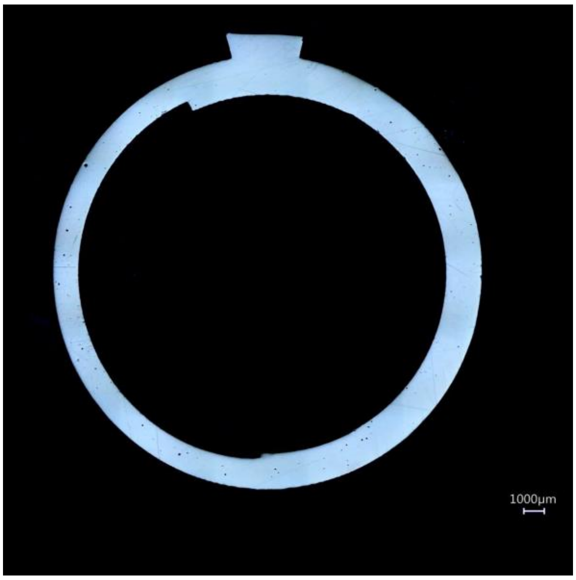

Figure 59 *Cast band model 4*

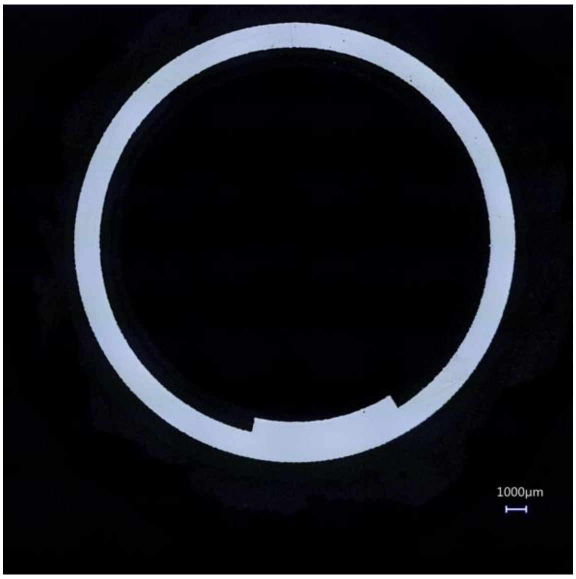

Figure 60 *SLM™ band model 4*

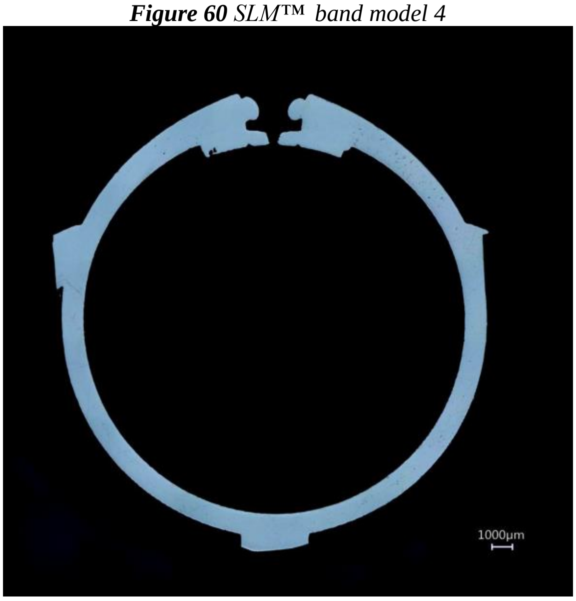

Figure 61 *Cast solitaire model 4*

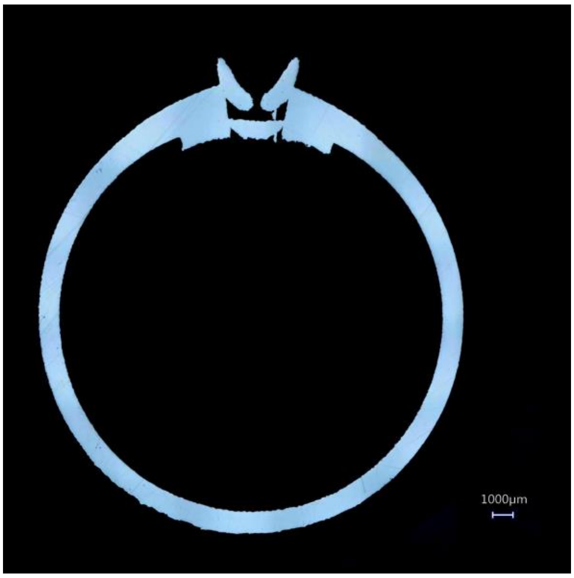

Figure 62 *SLM™ solitaire model 4*

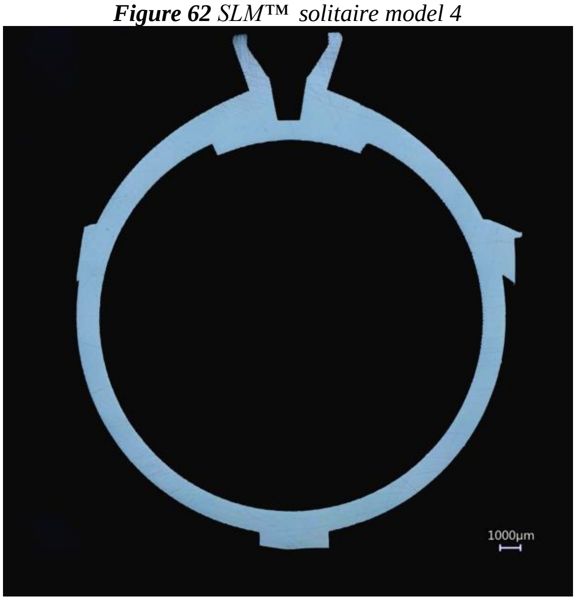

Figure 68 *Cast solitaire model 5*

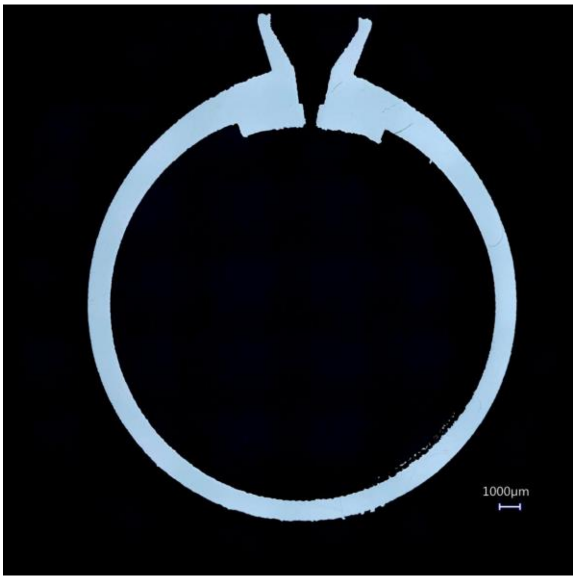

Figure 69 *SLM™ solitaire model 5*

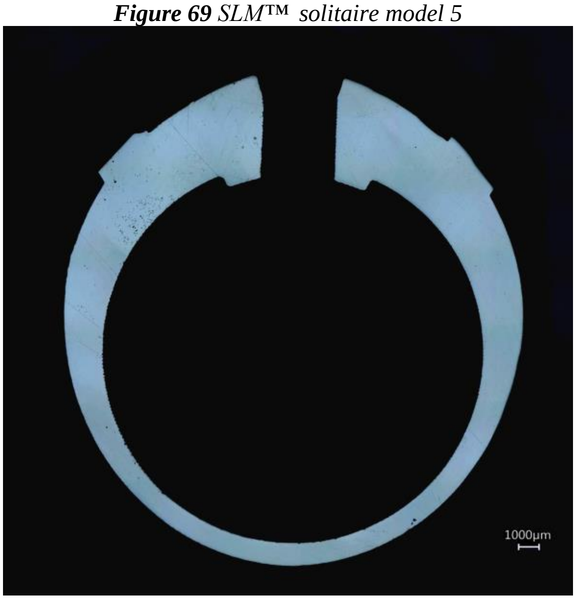

Figure 70 *Cast solitaire model 7*

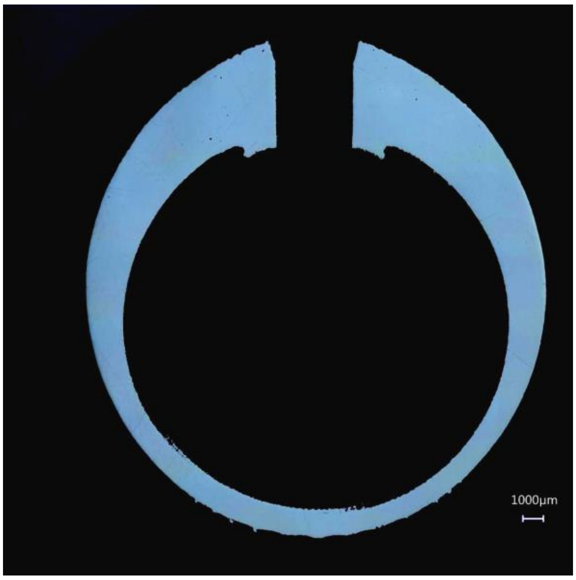

Figure 63 *SLM™ solitaire model 7*

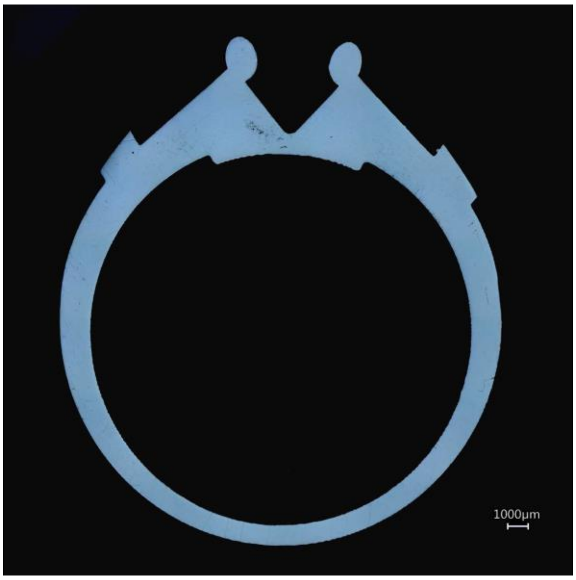

Figure 64 *Cast solitaire model 8*

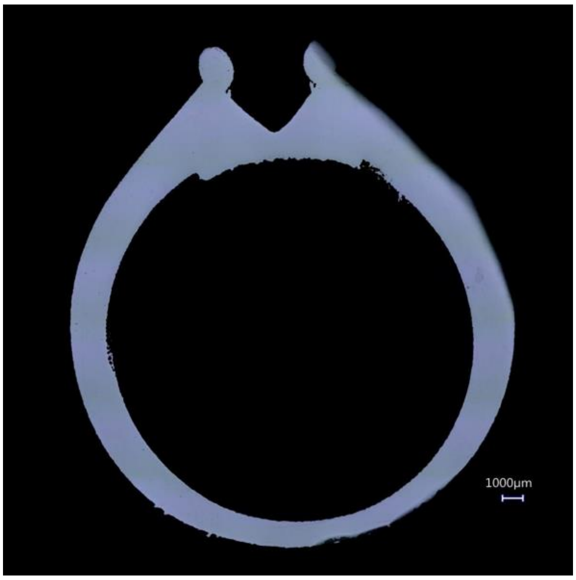

Figure 65 *SLM™ solitaire model 8*

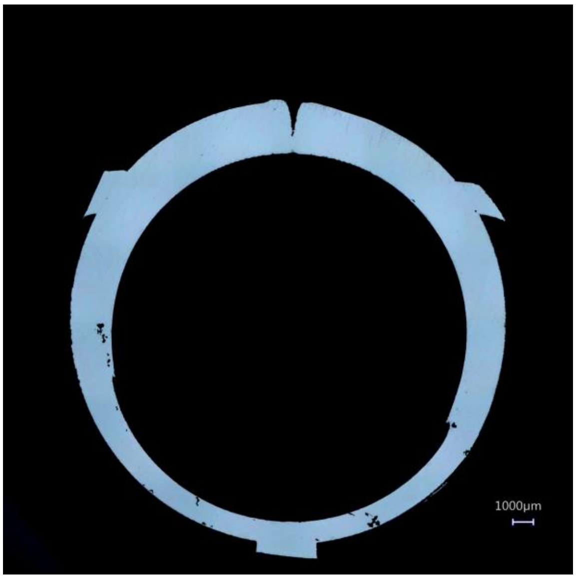

Figure 66 *Cast Solitaire model 15*

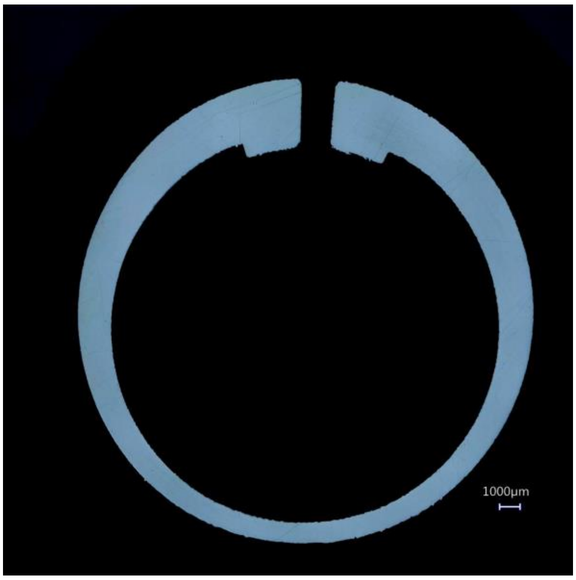

Figure 67 *SLM™ solitaire model 15*

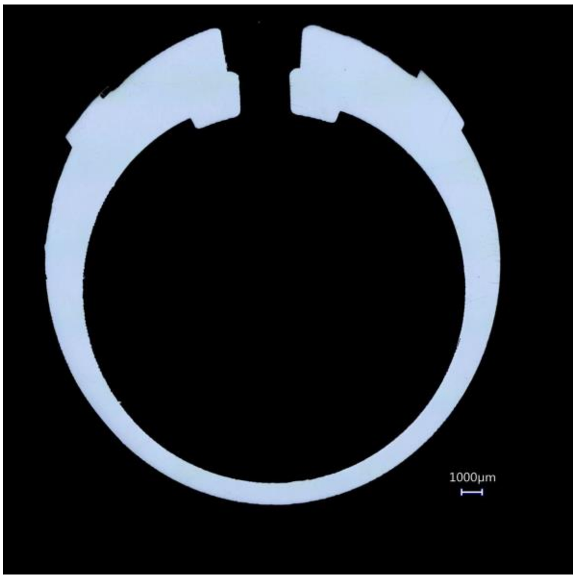

Figure 68 *Cast solitaire model 16*

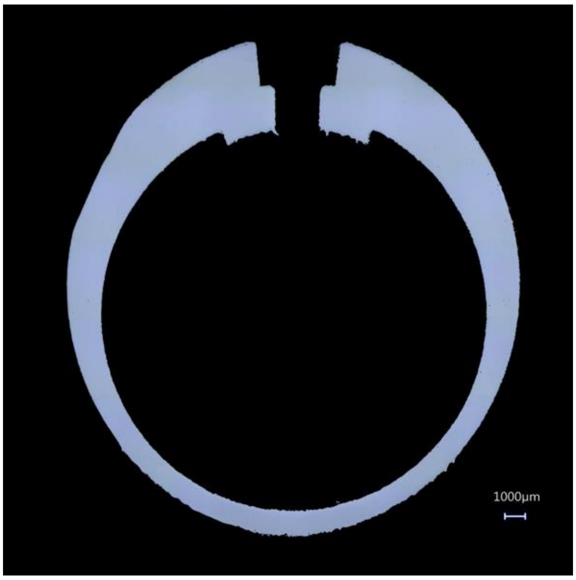

Figure 69 *SLM™   solitaire model 16*

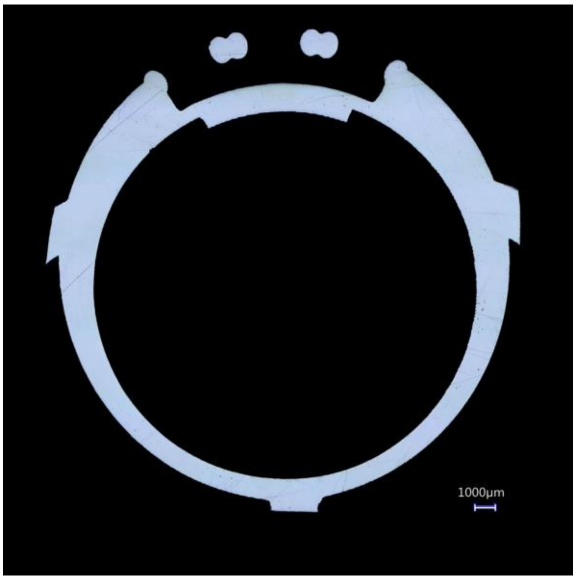

Figure 70 *Cast trilogy model 1*

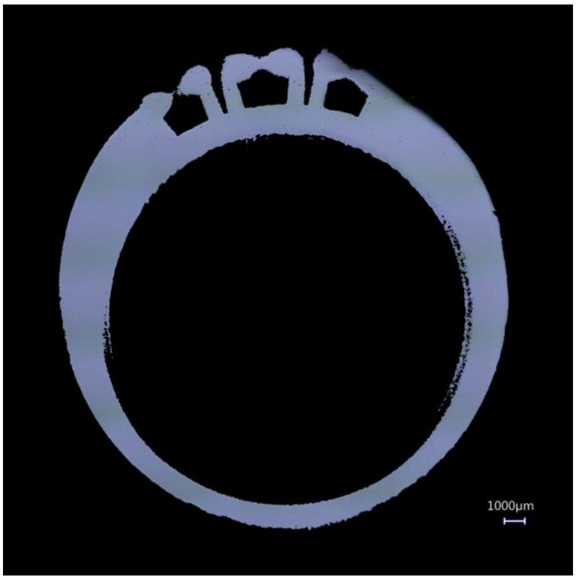

Figure 71 *SLM™ trilogy model 1*

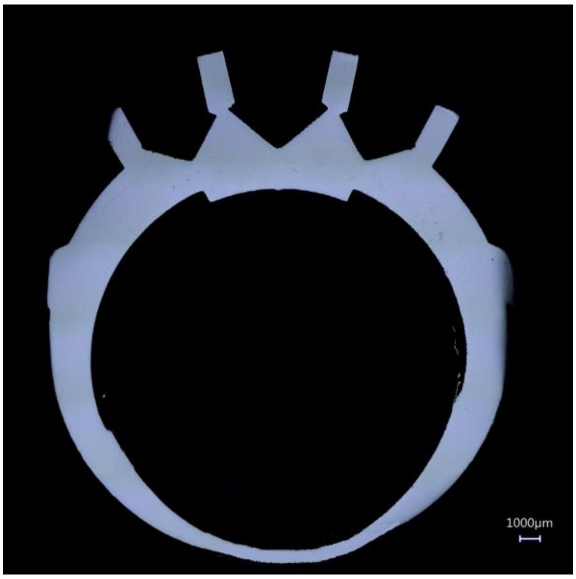

Figure 72 *Cast trilogy model 2*

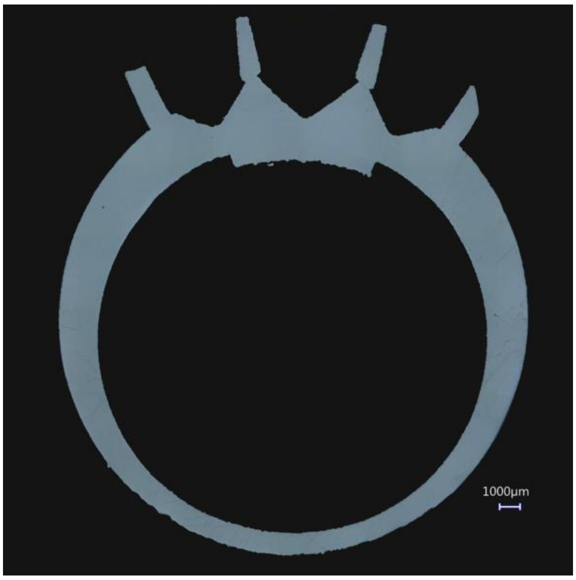

Figure 73 *SLM™ trilogy model 2*

Table 4 *Average percent porosity determined for the two production techniques of this case study*

Porosity (%)		
Model	**Casting**	**SLM™**
Band 1	0.05	0.016
Band 4	0.15	0.13
Solitaire 4	0.17	0.03
Solitaire 5	0.03	0.04
Solitaire 7	0.16	0.07
Solitaire 8	0.11	0.06
Solitaire 15	0.32	0.04
Solitaire 16	0.01	0.03
Trilogy 1	0.05	0.14
Trilogy 2	0.19	0.05

Average	0.13	0.06

The level of porosity determined ~~on~~ in the pieces can be quantified as medium-low in both cases, with values considerably lower for the SLM™ relative to casting, that presents a porosity that is two times that of SLM™ . For both cases, a noteworthy variability is present between different pieces and between different zones of the same piece with some sections that present an almost full density while others show a higher porosity. In casting, zones with a single but larger porosity (Figure 82) and zones with small but numerous porosities were observed (Figure 83).

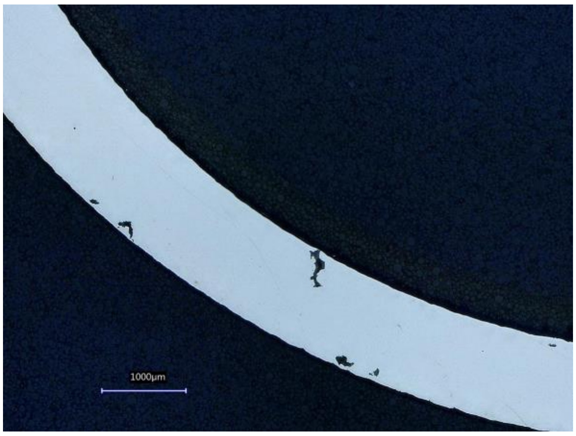

Figure 74 *Cavity in a section of a cast ring*

Figure 75 *Shrinkage porosity in a section of a cast ring*

The porosity in SLM™ never appears as cavity porosity but as single spherical pores, probably gas porosity (Figure 84), or zones with widely dispersed small voids (Figure 85) due to incomplete fusion between different laser scans.

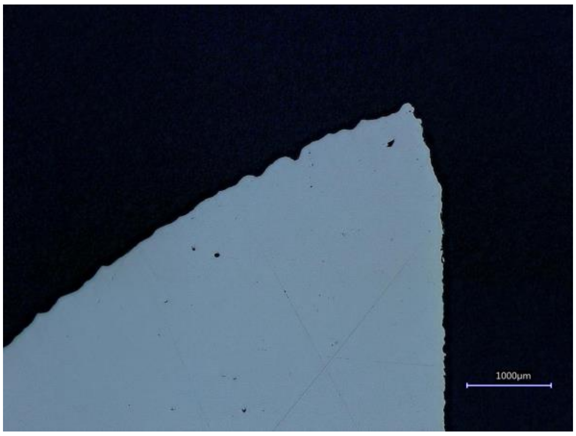

Figure 76 *Gas porosity in a section of an SLM™ ring*

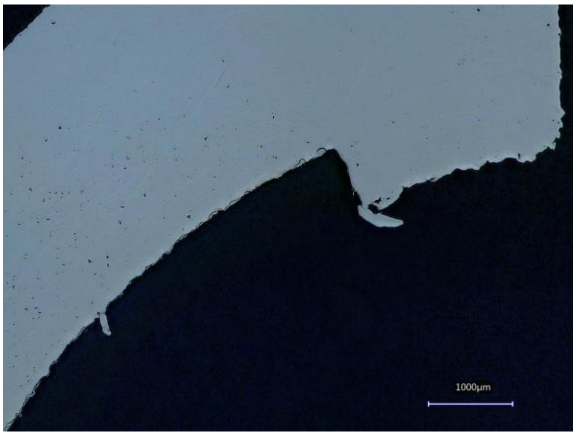

Figure 77 *Inter-hatch porosity in a section of an SLM™ ring*

Besides the percentage of porosity on the whole piece, the localization of the pores is also extremely important. Samples presenting a dense interior but with surface porosity are harder to finish than pieces presenting more porosity but with a more compact surface. From this point of view, it can be seen how the porosity found in some SLM™ pieces was mainly internal and rarely on the surface. This effect directly derives from the fusion and growth sequence of the jewel. Inside one single layer, the external surface is, in fact, fused as a single boundary and the laser parameters are optimized to guarantee an almost total absence of porosity inside each single fused track. The internal part of the jewel is subsequently fused with parallel laser scans~~ions~~. Porosities tend to concentrate at the junction points between the internal scans or between boundary and core. These zones are generally found 150 to 200 µm from the ring surface, hence allowing for polishing without exposing internal porosity.

In casting, the distribution of the porosities is more varied. Macroscopic superficial cavities can be seen on the external surfaces, mainly caused by detachments of refractory material, as well as shrinkage porosity that seems more concentrated inside the pieces. It is also worth noting the fracture in one of the cast bands. In this case porosity, even if concentrated inside the ring, covered such an extent that the mechanical integrity of the piece was compromised.

Metallographic Considerations

For the evaluation of grain dimension in both cast and SLM™ rings, metallography was carried out on the model 1 band ("as cast" and "as print"). This comparison confirms what was already observed in the past for gold and platinum alloys: the average dimension of the crystalline grains is drastically larger in cast pieces (Figure 86 and Figure 87) than in SLM™ pieces (Figure 88 and Figure 89). For SLM™ , it is possible to distinguish the signs left by each single laser scan but not each grain, per se, even at high magnification.

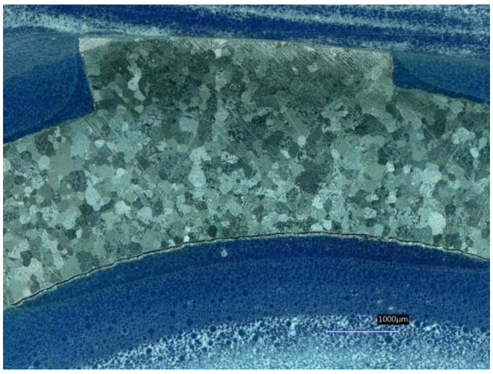

Figure 78 *As-cast band after etching, 50X*

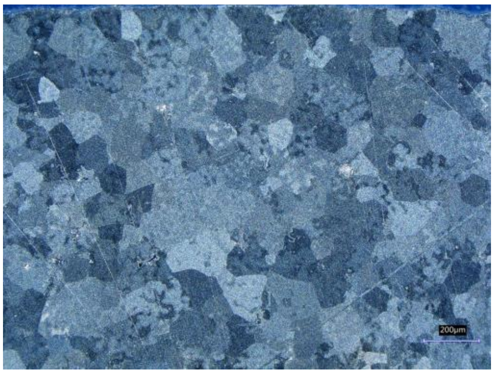

Figure 79 *As-cast sample, 200X*

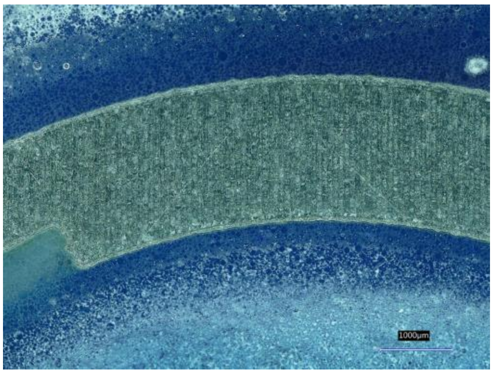

Figure 88 *"As-print" SLM™ band after etching, 50X*

Figure 89 *"As-print" SLM™ sample, 200X*

The presence of micro-cracks was observed in the SLM™ sample after (see e-mail) etching (Figure 90). The mechanical tests shown in the following paragraph were performed to evaluate the effective impact that this defect actually has on the properties of SLM™ pieces.

Figure 80 *Micro-cracks observed in the SLM™ band after etching*

Mechanical Characteristics

The mechanical characteristics of a jewel such as hardness, deformation and ultimate tensile strength have a direct influence not only on the pure mechanical resistance of the piece but also on the technological parameters such as the difficulties in setting and polishing. For this reason, the mechanical performance of the pieces produced were compared by considering the same alloy. The hardness test was carried out on band model 1 “as cast” and “as print” after solution annealing (1h at 1150°C/2102°F) and after age hardening (1h at 650°C/1202°F) using a Vickers Future-Tech hardness tester. The load values at breakage (UTS) and ductility (Elongation %) were determined through tests effected on an Instron dynamometer on samples that were especially produced for this specific test (Figure 91). Samples were tested both “as-cast” and “as-print” and after having been annealed in order to evaluate the possible mechanical differences that can influence during setting.

Figure 81 *Tensile test sample*

Table 5 *Vickers hardness of model 1 bands "as print" and "as cast"*

	Hardness [$HV_{0.5}$]		
	As cast / print	**Annealed**	**Age hardened**

CASTING	199 ± 3	188 ± 3	295 ± 2
SLM™	222 ± 4	180 ± 4	265 ± 6

The highest hardness determined for the "as print" compared to the "as cast" is in all probability the result of the smaller crystalline grain of the SLM™ pieces and the presence of more internal stresses in the printed samples, Annealing, in the case of the alloy employed, has the doubled effect of lowering the residual stresses and to solutionize, decreasing the hardness below 190 HV for both SLM™ and cast, which facilitates setting. After age hardening, in both cases hardness is noticibly increased, though more in the case of cast pieces. This could mean that resistance to wear during use could be higher for the cast pieces than in the case of SLM™ pieces. The observed difference could be due to the presence of micro-cracks seen on the etched sections and that favors the penetration of the indentator.

Table 6 *Mechanical characteristics*

	UTS (MPa)	**% Elongation**
Cast, as cast	531	19.5
Cast, annealed	498	21
SLM™ , as print	582	14.5
SLM™ , annealed	513	29.5

Regarding tensile testing, the samples produced through SLM™ "as print" exhibited a higher ultimate tensile strength than the "as cast" samples but with the drawback of presenting a lower ductility. After the annealing heat treatment, the ultimate tensile strength remains higher for SLM™ . Regarding elongation, though in both cases ductility is in fact increased after annealing, the increase in the case of SLM™ is noticeably higher.

Consequently, after annealing, SLM™ pieces present not only an ultimate tensile strength that is higher, but they can also be subjected to a higher percentage of deformation before breaking. This indicates that probably the fissures observed during etching have less impact on the mechanical characteristics of the samples than grain dimension and eventual internal defects present in the cast pieces. A better performance after annealing implies an improved behavior of the pieces during setting.

Filing, Sanding and Polishing: Impressions

Sector operators' impressions play a fundamental role in the possible success of a new productive technique. The production of jewelry does not escape this rule: Even if the quality of a product can appear excellent from a technical point of view, if during production workers are not convinced, this technique probably won't be adopted in the future. For this reason, the evaluation of the workers in charge of finishing the jewel was considered of great importance. In this way the more quantitave data (i.e., time and finishing losses) could be coupled to a more subjective one that is nonetheless fundamental to the evaluation. The 80 rings produced that were not destined for destructive tests were thus finished and evaluated. Each of the working phases was assessed by the same worker for casting and SLM™ as to have the same qualitative judgement for both techniques.

The first phase of the finishing process is the removal of the additional elements that are not part of the ring but that are necessary for its production, in other words, feeders and supports. It can be seen from the workers' opinions, Figure 92, that some SLM™ models present a higher difficulty, in particular for the solitaire model 4 (Figure 18) and the trilogy model 1 (Figure 24), where supports are also present on inner surfaces. Removing supports from the inside of the piece requires a higher dexterity of the operator and the chances of the piece being damaged in this phase are higher.

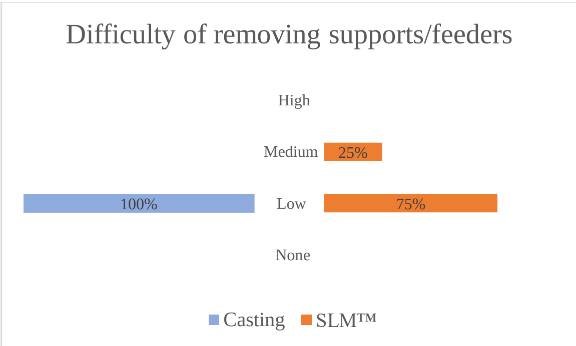

Figure 82 *Assessment of the difficulty in removing feeders/supports*

Similar results for cast and SLM™ pieces were recorded instead during the evaluation of filing and sanding (Figure 93). The difficulty, which depended on both roughness and surface compactness, turned out to be low for about 80% of both techniques. The only difference of importance is the presence of one casted ring particularly difficult to file and sand, then discarded as non-conformal. The appraisals are somewhat interesting if one considers that one of the weakests points of selective laser melting is the elevated surface roughness. The opinion given by the workers regarding this last point is that applying greater force or using coarser sandpaper manages to eliminate the added surface roughness with just slightly increased effort. This effort, however, is compensated for by the superior quality of the SLM™ metal (Figure 94). The percentage of surfaces deemed optimal in SLM™ from a compactness point of view is close to 100% while in casting the evaluation is more varied since only 63% of the surfaces are considered optimal, 23% of a medium quality, about 10% of low quality due to porosity and two rings that were classified as non-conforming.

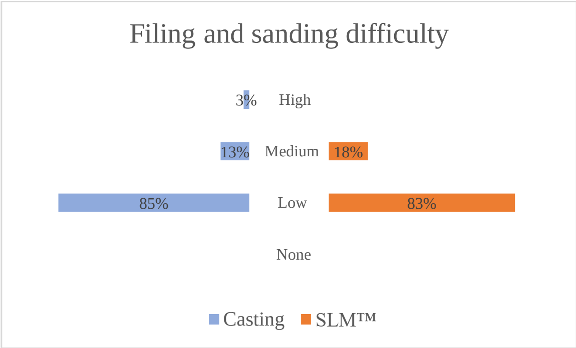

Figure 83 *Evaluation of filing and sanding difficulty*

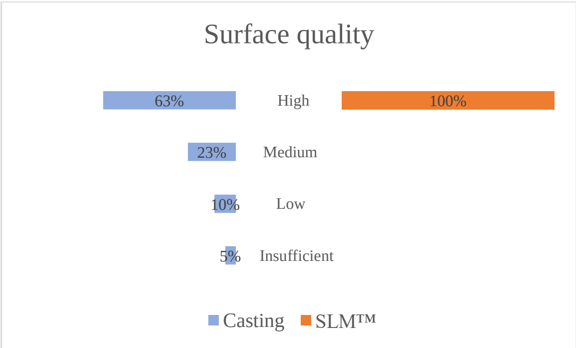

Figure 84 *Evaluation of superficial quality after filing and sanding*

No particular difference was observed during polishing (Figure 95), with the level of difficulty defined as low or nonexistent (Figure 96) in both cases. The mechanical properties of the metal are thus deemed more than good for both techniques.

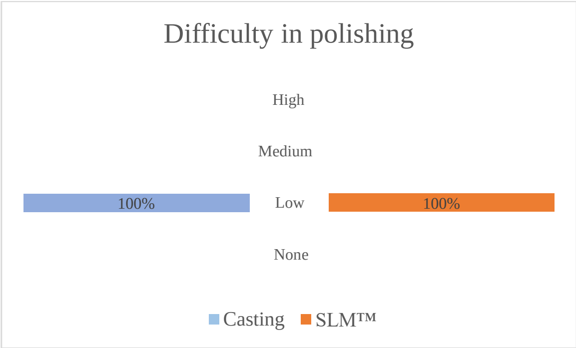

Figure 85 *Evaluation of polishing difficulty*

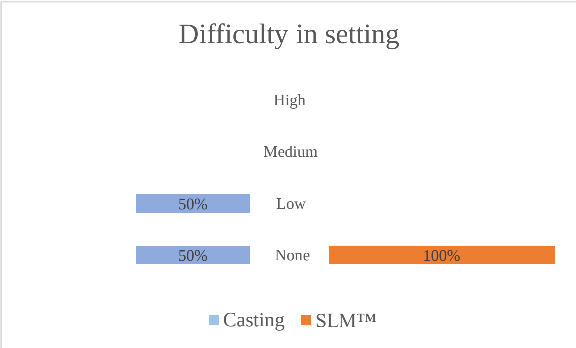

Figure 86 *Evaluation of setting difficulty*

QC: Evaluation

The judgement of QC is fundamental to understand if the jewelry produced is conforming accordingly to the criteria of residual porosity and aesthetics fixed for high-end jewelry. Consequently, the rings were divided into three groups: those that directly passed the control test, those that needed to be repaired by laser, and those that were deemed non-repairable. The diversity of results between SLM™ and casting is noticeable: About three quarters of the printed rings immediately passed the test, while only half of the cast ones obtained the same results (Figure 97).

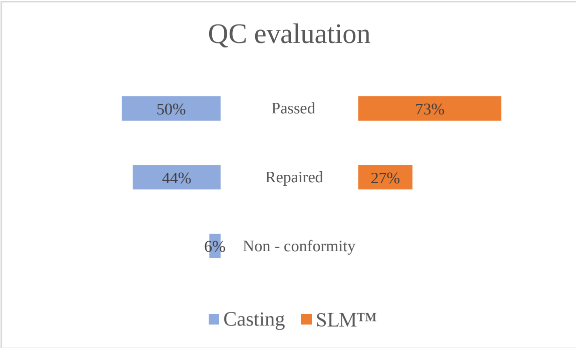

Figure 87 *Evaluation by the QC department of Stilnovo of the pieces*

The opinions given by the quality control department confirm the data obtained about the macroscopic defect and through internal porosity analyses of the sacrificial samples: The pieces produced through SLM™ are less defective than the cast pieces. Regarding non-conformity, not a single SLM™ piece was considered as such while two of the cast pieces were classified as non-repairable in addition to the band with the cracked shank among the sacrificials rings.

The final appearance of the ten ring models after polishing and setting is visible in Figure 98, 99 and 100 for casting and in Figure 101, 102 and 103 for SLM™.

Figure 88*. Casted solitaires*

Figure 89. *Casted trilogies*

Figure 100. *Casted bands*

Figure 101. *3D printed solitaires*

Figure 90. *3D printed trilogies*

Figure 91. *3D printed bands*

ECONOMIC AND FINANCIAL EVALUATION

Production Times for the Semi-finished Samples

Times for each step in real-life production were measured for both SLM™ and casting. The casting production was divided into 11 trees, listed in

. The burnout cycles of the flasks, which represents the longest productive phase in casting, were grouped in order to achieve the best compromise between scrap recovery and productive times. To reproduce what happens in real production, it was decided to reuse the production scraps by adding it to fresh alloy and thus reducing the total amount of metal in process. This procedure is usually employed to limit the quantity of precious metal required not only because of the cost of the precious metal but also because of the cost of refining. Particularly, in the case of the first four trees, only fresh alloy was used, while for the second set of three and the last four, a mix of scraps and fresh alloy was utilized.

Table 7 *Division of the castings*

N° flasks	Cast pieces	Burnout cycle
1	3 solitaire 4	1
2	2 solitaire 4 + 2 solitaire 5 + 1 solitaire 15	1
3	2 solitaire 5 + 3 solitaire 16	1
4	2 solitaire 16 + 3 solitaire 15	1
5	5 female bands + 1 solitaire 5	2
6	1 female band + 6 male bands	2
7	1 solitaire 5 + 2 solitaire 8	2
8	2 solitaire 8 + 1 solitaire 7 + 3 trilogy	3
9	1 solitaire 7 + 4 trilogy	3
10	2 solitaire 8 + 4 solitaire 7	3
11	5 trilogy + 1 solitaire 16	3

For SLM™ , the production was divided among seven printing tables (**Error! Reference source not found.**), made in decreasing order of the height of the objects produced. This allows the optimization of the powder by producing first the tallest pieces because more powder is required to fill the printing space for taller pieces.

Table 8 *Division of the prints and production time*

N° table	Printed pieces	Printing time (h)
1	6 solitaire 4 + 6 solitaire 15	12:40
2	6 trilogy 1 + 6 trilogy 2	14:00
3	6 solitaire 5 + 6 solitaire 8	11:30
4	6 solitaire 7 + 6 solitaire 16	14:10
5	3 female band 1 + 2 male band 1	4:45

6	3 female band 4 + 2 male band 4	4:30
7	1 male band 1 + 1 male band 4	2:30

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The average casting production time for each single flask and the total time each machine was in use are listed in

Table 10 *Average and total time for machinery and operator for the production of SLM™ rings*

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lists the average times for each printing table and the total time the SLM™ machines were in use. Furthermore, the time required by the operators was also registered. A higher total number of human hours not only increases production costs but also implies less possibility to automate the process.

Table 9 *Average and total time for machinery and operator for the production of cast rings*

Cast Production Time [min]				
Production phase	**Machinery time per flask**	**Total machinery time**	**Operator time per flask**	**Total operator time**
Feeders design	11	120	11	120
Wax production	38	420	2	15
Feed sprue elimination	33	360	2	20
Tree mounting	10	110	10	110
Flask preparation	-	-	10	110
Investment preparation	6	65	6	65
Burnout cycle	188	2075	-	-
Casting	15	165	15	165
Investment removal	20	220	20	220
Sandblasting	2	20	2	20
Separation from tree	-	-	10	110
Solution annealing	10	120	10	15
Age hardening	6	60	6	5
TOTAL (Approx.)	330 (5.5 h)	3750 (62.5 h)	90 (1.5 h)	990 (16.5 h)

Table 10 *Average and total time for machinery and operator for the production of SLM™ rings*

SLM™ Production Time [min]				
Productiom phase	**Machinery time per table**	**Total machinery**	**Operator time per table**	**Total operator time**
Supporting	40	290	40	290
SLM™ equipping	10	70	10	70
Print	550	3840	-	-
Machine cleaning	10	70	10	70
Support elimination	-	-	36	250
Solution annealing	17	120	2	15
Age hardening	7	60	1	5
Shot peening	11	75	11	75
TOTAL (Approx.)	645 (10.75 h)	4530 (75.5 h)	110 (1.8 h)	780 (13 h)

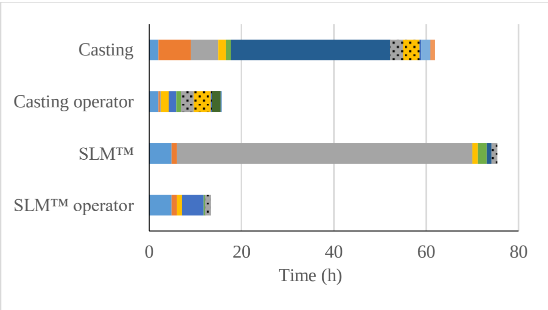


Figure 104. *Total machinery times for each technique and total operator hours*

From the data shown in Figure 104, it is possible to understand that the machine time is about 20% longer for printing than for casting. In both cases ~~a~~ one production phase required an especially long machine time. With casting the burnout cycle takes up 55% of the total production time while in SLM™ the printing time takes up 85% of the total production time. These phases, however, do not require the assistance of a human worker and add to the costs only in terms of machinery usage and electric energy consumption.

By looking at the human hours, the situation is the opposite: Even if SLM™ requires more machinery time, it also requires less operator time (-20%) compared to casting. This means that this technique lends itself towards automation.

Another important data point for the evaluation of a production technique is the total production time, which is considered as the time needed to produce a jewelry lot. This time consists of a 9-hour work day (four hours morning and afternoon with a one hour lunch break), five days a week as well as the processes that can continue at night because they do not require supervision. In addition, the waiting times and the times in which more than one task can be carried out simultaneously are also considered (i.e., pickling, drying of the flasks, etc.).
The hourly division of the production phases in casting and SLM™ are shown in **Error! Reference source not found.** and 13, showing the sequence that was in fact followed during production. This contains the subdivision in three flask groups in casting in order to use less precious metal through the recycling of scraps, and in SLM™ , printing the tallest tables first, followed by shorter configurations in order to use less powder.

Table 11 *Time division of the casting production phases*

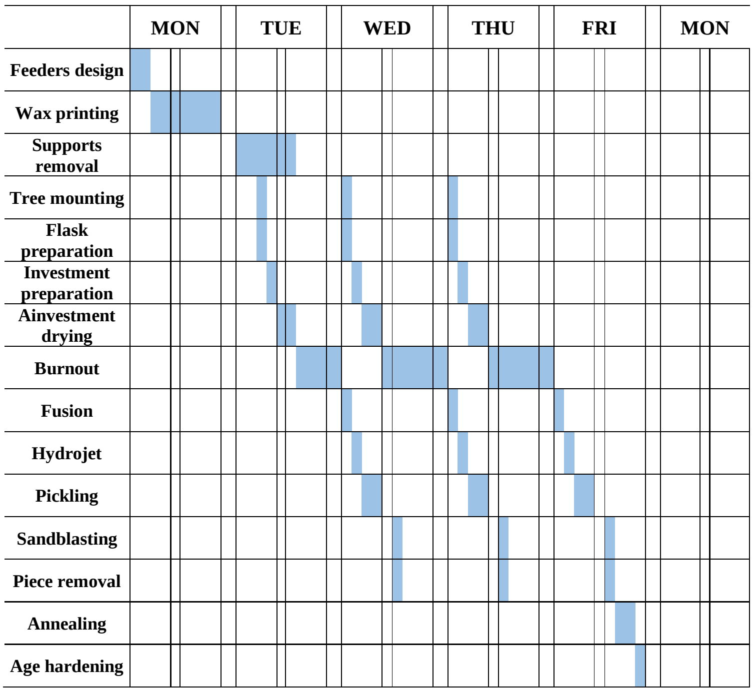
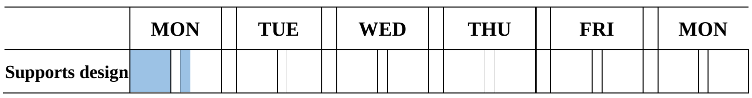
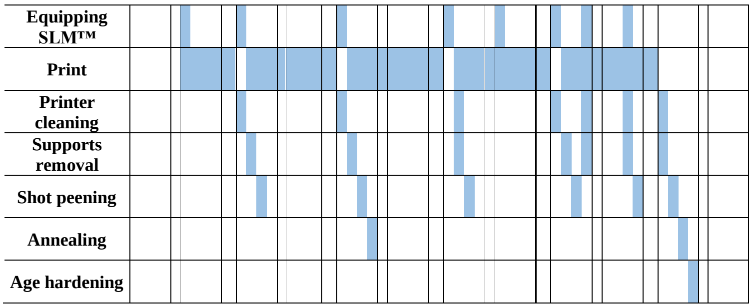


Table 12 *Time division of the production phases in SLM™*





The total production time is equal to ~~5~~ five working days for casting and five and a half working days for SLM™ . It has to be considered, though, that the work carried out on the sixth day for SLM™ includes the beginning of the production of a second lot because that work can be carried out simultaneously. This means that with consecutive lots of 60 rings, such as the one presented in this study, production times can be considered almost identical.

Finishing Times

Total finishing times (Tables 14 and 15) were reported separately from the production time because they consist of the same processes independent~~ly~~ of the manufacturing technique employed. The discriminating characteristics in this phase are the difficulty of removing the feeders and support residuals and the quality of the samples in terms of roughness, surface compactness and residual porosity. Generally, the presence of porous or irregular surfaces makes the operator remove more material before reaching a more compact zone of the jewel, which means that longer operational hours are required and losses are greater.

Table14 *Time (in minutes) of the finishing operations for cast rings*

	Feeder elimination	Filing & sanding	Pre polishing	Setting	Polishing	Total
Band 1	1	50	-	-	10	60
Band 4	1	45	-	-	10	60
Solitaire 4	1	85	5	60	10	160
Solitaire 5	1	70	5	20	10	105
Solitaire 7	1	45	5	30	10	90
Solitaire 8	1	80	5	30	10	130
Solitaire 15	1	110	5	30	10	155
Solitaire 16	1	60	5	20	10	100

Trilogy 1	1	170	5	90	10	275
Trilogy 2	1	110	5	90	10	215

Table 15 *Time (in minutes) of the finishing operations for SLM™ rings*

	Supports removal	**Filing & sanding**	**Pre polishing**	**Setting**	**Polishing**	**Total**
Band 1		50	-	-	10	60
Band 2		45	-	-	10	60
Solitaire 4	2	90	5	45	10	150
Solitaire 5	2	55	7	25	10	100
Solitaire 7	2	55	7	30	10	100
Solitaire 8	3	100	7	30	10	150
Solitaire 15	1	75	5	30	10	120
Solitaire 16	2	60	8	20	10	95
Trilogy 1	4	200	5	90	10	310
Trilogy 2	1	125	5	90	10	230

By analyzing the time required for removing feeders and supports, it can be seen that on average the castings appear to be a faster operation due to the relative simplicity of the geometries of the rings in the feeding zones to be reconstructed. The average time required in this phase is also more uniform in the case of casting while in the case of SLM™ the variability increases according to the positioning of the supports, with longer times for the models in which removal was considered more complex by operators.

By observing the filing and sanding times, it seems evident that, with few exceptions, the printed rings required the same or even less time to complete than those cast. This data is in accordance with opinions given regarding this phase, as shown in Figure 93, since the printed rings seem equally difficult to work compared to the cast ones while leaving a better surface quality.

Polishing did not reveal substantial differences between the techniques regarding work times, and the same can be concluded for setting with the exception of solitaire model 4, which registered a longer time for ~~than~~ the cast model.

While repairs were needed on more of the castings than printed parts, the total time required for this operation on the casted rings was only slightly longer.

Finishing Losses

The material removed from the rings during finishing has a direct impact on the production costs since it cannot be completely recovered. In Table 16 the average values of loss for each model produced and each manufacturing process used during finishing are shown.

Table 16 *Finishing losses in grams*

	Casting	SLM™
Solitaire 4	1.36	0.92
Solitaire 5	0.62	0.56
Solitaire 7	0.82	1.09
Solitaire 8	0.62	0.98
Solitaire 15	2.18	1.75
Solitaire 16	0.87	0.96
Trilogy 1	0.88	0.93
Trilogy 2	1.08	1.05
Female Band 1	0.86	1.37
Male Band 1	1.18	1.47
Female Band 4	1.00	0.93
Male Band 4	1.07	1.33

The total losses are higher in either SLM™ or casting depending on the model that is being considered. However, by analyzing the single phases it can be seen that during removal of the feeders, the losses from casting are always higher than in SLM™ , while filing and sanding show more losses in selective laser melting. These results can be easily explained through the quantity of residuals that feeders and supports leave in each case and through the elevated surface roughness that SLM™ pieces present after printing. The impact of the recorded losses in terms of production costs, assuming a loss of 5% during recuperation of the scraps, is summarized in Table 17.

Table 17 *Impact of material loss on production costs*

	Cost of losses	
	Casting	SLM™

Solitaire 4	1.7 €	1.2 €
Solitaire 5	0.8 €	0.7 €
Solitaire 7	1.0 €	1.4 €
Solitaire 8	0.8 €	1.2 €
Solitaire 15	2.7 €	2.2 €
Solitaire 16	1.1 €	1.2 €
Trilogy 1	1.1 €	1.2 €
Trilogy 2	1.4 €	1.3 €
Female Band 1	1.1 €	1.7 €
Male Band 1	1.5 €	1.8 €
Female Band 4	1.2 €	1.2 €
Male Band 4	1.3 €	1.7 €

Raw Materials and Refining Costs

For a correct evaluation of the final cost of the ring production, the difference in the cost of raw materials was also taken into consideration. The two production techniques, in fact, differ from one another through the price of the raw materials and the number of times they have to be refined to produce the same quantity of jewels. Regarding the cost of raw materials, by assessing market prices it was estimated that the cost for acquiring new raw materials for SLM™ was 0.3 €/g higher than for casting due to the higher cost of atomization compared to granulation. The same cost difference was assumed also between the granulation and the atomization of new material from the refined platinum. In order to evaluate the impact of refining cost, the ratio of pieces produced to reject pieces was first calculated. The recorded weights and the percent of yields are shown in Table 18 for casting and in Table 19 for selective laser melting.

Table 18 *Percent yield of casting*

Casting Production Yield (%)			
N° flask	**Total weight (g)**	**Pieces net weight (g)**	**% yield**
1	125.17	16.08	13
2	158.46	30.76	19
3	150.18	38.25	25
4	179.82	48.22	27

5	140.39	42.57	30
6	150.45	59.31	39
7	180.98	42.46	23
8	185.35	52.84	29
9	180.13	54.06	30
10	190.29	63.58	33
11	196.59	54.49	28
TOTAL	1837.81	502.62	27

Table 19 *Percent yield of SLM™*

SLM™ PRODUCTION YIELD (%)			
N° table	**Total weight (g)**	**Pieces net weight (g)**	**% yield**
1	150.06	91.5	61
2	173.28	113.52	66
3	138.18	84.30	61
4	181.5	125.58	69
5	59.7	42.49	71
6	52.74	40.3	76
7	24.1	18.04	75
TOTAL	779.56	515.73	68

The different yields for the two production processes have a direct influence on the amount of refining necessary for each one and consequently on the whole production cost as well. The calculation of costs due to refining was done assuming that:

- The 60 rings produced for this study are a typical production lot, close to 500 g of rough jewels. During production of the 60 cast rings, the scraps were reused two times and started with 1 kg of alloy. It is assumed that all scrap has to be refined after one production lot, that means after two re-melting.
- To consider the situation in SLM™ similar to that of casting, it is assumed that all scraps have to be refined after being re-used two times. For this study the 3D printer was initially fed with 2.8 kg of powder, a standard production condition.

- The refining costs, both fixed and variable according to the quantity of material, were calculated from the average price given by six different suppliers in the Italian market (Table 20).

Table 13 *Average refining costs in the Italian market*

Average Refining Costs		
Price €/kg	Fixed price	Loss
331 €	90 €	12 ‰

Focusing on SLM™, given the initial quantity of powder in the printer, it is not necessary to re-melt any scrap during production of a single lot. At the end of the first lot printing, the quantity of powder in the printer is about 2 kg, the rest being used for rings (500 g) and supports (300 g). The second lot can also be produced without reusing scraps. In order to continue with a third production lot, it is necessary to atomize the scraps (made up principally of the supports) and add 1000 g of new powder in order to fill the printer platform up to the total height of the pieces to be printed. The use of recycled metal two times is only necessary for the production of the fifth lot, and after the sixth all the powder has to be refined. To start the production of the seventh lot, 1000 g of new powder must be added.

The data relative to the required powder for production through SLM™ and the material to be refined is reported in Tables 21 and 22.

Table 21 *Material to be refined using SLM™*

	1° lot	**2° lot**	**3° lot**	**4° lot**	**5° lot**	**6° lot**
Powder from refined material [g]	0	0	0	0	0	0
Powder from remelted scraps [g]	0	0	600	0	600	0
Powder to be bought [g]		0	1000	0	1000	0
Total powder before production [g]	2800	2000	2800	2000	2800	2000
Produced pieces [g]	500	500	500	500	500	500
Reusable scraps [g]	300	300	300	300	0	0

Scraps to be refined [g]	0	0	0	0	300	300
Total powder after production [g]	2000	1200	2000	1200	2000	1200
N° of scrap atomizations	0	0	1	1	2	2
Total produced pieces [g]	3000					
Total n° of refinings	1					
Total powder to be refined[g]	1800					
Total powder bought [g]	2000 + 1000					

Table 22 *Refining cost using SLM™*

SLM™ Costs	
Refining	1 x 598 €
Analysis	1 x 90 €
Loss	1 x 540 €
Total refining cost	1228 €
Refined powder atomization	1440 €
New powder atomization	2400 €
Total	5065 €
€/g	1.69

For comparison, calculations for refining costs and raw materials for the production of the same amount of pieces by casting were made, taking into consideration that after each lot of 500 g it is necessary to refine 0.5 kg of scraps (Tables 23 and 24).

Table 23 *Material to be refined with casting in grams*

	1° lot	**2° lot**	**3° lot**	**4° lot**	**5° lot**	**6° lot**

Alloy from refined material [g]	0	500	500	500	500	500
Alloy from remelted scraps [g]	0	0	0	0	0	0
Alloy to be bought [g]		500	500	500	500	500
Total alloy before production [g]	1000	1000	1000	1000	1000	1000
Produced pieces [g]	500	500	500	500	500	500
Reusable scraps [g]	0	0	0	0	0	0
Scraps to be refined [g]	500	500	500	500	500	500
Total alloy after production[g]	0	0	0	0	0	0
N° of scrap atomizations	2	2	2	2	2	2
Total produced pieces [g]	3000					
Total n° of refinings	6					
Total alloy to be refined [g]	6 x 500					
Total alloy bought [g]	2500 + 500					

Table 24 *Refining costs using casting*

Casting Costs	
Refining	6 x 165 €
Analysis	6 x 90 €
Loss	6 x 150 €
Total refining cost	2434 €
Refined alloy granulation	1500 €
New alloy granulation	1500 €
Total	5434 €

€/g	1.81

Despite the lower cost of raw material, the cost per gram of jewel produced is 7% higher in the case of casting, mainly because of the fixed costs applied to refining, which correspond mainly for assaying. Naturally, these costs have to be added to hours of machinery usage, to the operators' hours and to the energy consumption in order to have an accurate picture of the cost per gram using each technique.

Production Costs of Rings

The data presented in the preceding paragraphs, among which are production times, production lots and yields, allow one to calculate the industrial costs for the production of each single model. In order to do so, some assumptions were made so as to render the comparison as close to reality as possible:

1. The productive capacity for both techniques was calculated based on the effective usage of the machines and by considering the lot of rings produced for this case study as the weekly production.
2. A machine lifetime was chosen considering the average fiscal amortization that is currently valid in Italy (5 years). The lifetime was not considered in hypothetical working hours because, in all probability, all the machinery would become obsolete before reaching the end of its lifetime.
3. The costs related to consumables were divided equally among the produced objects by calculating the average cost and not the specific cost of each object.
4. For this study, the physical spaces for the production were omitted, even though the space needed for 3D printing is less. Same omission was applied to electrical and hydraulic plants that are needed for casting.
5. Disposal costs from casting (i.e., for crucibles, investment and acids) were not considered.
6. The benchmark was developed hypothesizing that the companies involved produce exclusively platinum. This implies a lower exploitation of resources that could be of common usage for gold, silver and platinum production.
7. The division of machinery and workers cost for each single model was done based on the weight percentage that each ring had with respect to the total weight of the tree or table.
8. Operators' hourly cost are considered as equal for SLM™ and casting and similar for every production and finishing step.

The consumable materials for SLM™ and casting production are shown in Table 25.

Table 25 *Consumable materials for production*

Resources	Unit Cost	Casting	SLM™
Wax for 3D printing rings	€ 0.70 / piece	€ 41.30	

Wax for 3D printing Supports	€ 0.51 / piece	€ 30.09	
Isopropyl alcohol supports removal	€ 0.97 / piece	€ 57.23	
Wax for sprues	€ 0.02 / piece	€ 1.18	
Investment	€ 0.80 / piece	€ 47.20	
Hydrofluoric acid	€ 0.20 / piece	€ 11.80	
Crucibles	€ 60.00 each	€ 100.00	
Argon gas	€ 1.70 / m^3	€ 2.81	€ 65.28
Electric energy	€ 0.14 / kWh	€ 32.16	€ 5.86
Total		€ 323.76	€ 71.14

The results of the production costs for each model were divided in production of the semi-finished product cost, finishing costs (including losses) and refining costs, which are shown in Tables 26, 27 and 28, respectively.

Table 26 *Production costs for each model in the semi-finished state*

Semi-finished Products Cost		
Model	**Casting**	**SLM™**
TRILOGY - 1	19.36 €	16.86 €
TRILOGY - 2	26.62 €	22.42 €
SOLITAIRE - 4	20.43 €	11.60 €
SOLITAIRE - 5	15.39 €	11.33 €
SOLITAIRE - 7	26.81 €	17.88 €
SOLITAIRE - 8	21.90 €	18.86 €
SOLITAIRE - 15	28.13 €	22.46 €

SOLITAIRE - 16	24.95 €	14.66 €
FEMALE BAND - 1	20.84 €	18.05 €
MALE BAND -1	20.12 €	20.93 €
FEMALE BAND - 4	21.96 €	17.71 €
MALE BAND - 4	19.66 €	20,68 €

Table 27 *Finishing costs for each ring model*

Finishing Costs		
Model	**Casting**	**SLM™**
TRILOGY - 1	91,14 €	102,26 €
TRILOGY - 2	69,96 €	74,92 €
SOLITAIRE - 4	52,52 €	49,97 €
SOLITAIRE - 5	34,96 €	33,64 €
SOLITAIRE - 7	37,08 €	35,57 €
SOLITAIRE - 8	43,54 €	49,81 €
SOLITAIRE - 15	51,12 €	40,70 €
SOLITAIRE - 16	33,11 €	32,75 €
BAND 1 FEMALE	20,52 €	19,21 €
BAND 1 MALE	21,89 €	19,66 €
BAND 4 FEMALE	19,07 €	14,44 €
BAND 4 MALE	15,91 €	22,40 €

Table 28. *Raw material and refining cost for each ring model*

Raw Material and Refining Costs

Model	Casting	SLM™
TRILOGY - 1	6.45 €	5.69 €
TRILOGY - 2	8.61 €	7.36 €
SOLITAIRE - 4	4.34 €	3.66 €
SOLITAIRE - 5	4.13 €	3.69 €
SOLITAIRE - 7	9.35 €	7.95 €
SOLITAIRE - 8	7.06 €	6.00 €
SOLITAIRE - 15	7.97 €	6.87 €
SOLITAIRE - 16	7.57 €	6.49 €
BAND 1 FEMALE	6.15 €	5.53 €
BAND 1 MALE	7.08 €	6.37 €
BAND 4 FEMALE	6.02 €	5.22 €
BAND 4 MALE	6.89 €	6.08 €

What emerges from the production costs of the semi-finished products is the great impact that the underuse of the casting plants has on ammortization, which renders it disadvantageous with respect to SLM™. This leads to a higher production cost for each ring model except for male wedding bands. This under-use derives from the common practice that many companies have of internalizing the casting of platinum for reasons that are more strategic than economical instead of delegating it to third parties. Furthermore, the segment of platinum jewelry is a niche with productive demand about 60 times lower with respect to gold demand, which contributes to a non-optimal usage of the casting plants.

The total finishing costs show a more varied profile, with a slight advantage for SLM™ pieces with the exception of the rings that present a higher difficulty of support removal and sanding of the support areas.

Regarding the refining costs, all models appear superior in SLM™ due to the higher cost per gram of the cast jewel.

By looking at the total costs (Table 29), the production of SLM™ presents itself as more economical compared to casting for 5 solitaries and the two female bands while Trilogy 1 and Band model 4 for males are less expensive when cast. For solitaire model 8, Trilogy model 2 and the male Band model 1, the costs are almost identical with both techniques since the determined difference can be easily nulled by small variations in the production phase. It is important to emphasize that the added cost related to the recasting of non-conforming rings was not taken into consideration. Consequently, only 57 cast rings are sellable as opposed to 60 SLM™ rings. In addition, the potential refusion of a non-conforming piece is less advantageous in terms of cost and time with respect to a hypothetical re printing.

Table 29 *Total cost per model per technique and cost difference between casting and selective laser melting*

Total Costs			
Model	**Casting**	**SLM™**	**Difference**
TRILOGY - 1	124.91 €	133,07 €	8,2 €
TRILOGY - 2	115.82 €	115,37 €	-0,4 €
SOLITAIRE - 4	82.65 €	70,53 €	-12,1 €
SOLITAIRE - 5	59.58 €	54,01 €	-5,6 €
SOLITAIRE - 7	86.40 €	72,92 €	-11,9 €
SOLITAIRE - 8	82.83 €	83,37 €	2,2 €
SOLITAIRE - 15	97.06 €	79,97 €	-17,1 €
SOLITAIRE - 16	74.98 €	63,31 €	-11,7 €
FEMALE BAND 1	55.10 €	50.80 €	-4.30 €
MALE BAND 1	57.83 €	56.19 €	-1.64 €
FEMALE BAND 4	54.48 €	44.93 €	-9.55 €
MALE BAND 4	50.96 €	57.97 €	7.01 €

Invested Capital

The required invested capital to initiate production ~~activity~~ of the semi-finished products that were the object of this study, is slightly higher for SLM™ than for casting (Table 30). In fact, the higher total cost of the casting machinery needed is not totally offset by the lower cost of a SLM™ plant because of the greater amount of metal needed for SLM™.

Table 30 *Invested capital required for the start-up of a semi-finished products company*

Resource	Cost

	Casting	SLM™
Rhinoceros	1,800 €	
Magics Materialize		17,000 €
Wax printer 3D systems Projet MJP	58,500 €	
Tub + mixer	840 €	
Injector Ewing Star	11,500 €	
Mixer st. Louis 2001	13,500 €	
Oven Tibaldi FC-M	9,200 €	
Casting Machine Yasui VCC	68,000 €	
Hydrojet Royaljet	2,000 €	
Oven Carbolite	5,000 €	5,000 €
Sandblaster MDM 60N-G.M.-H2100	4,500 €	
Printer SLM™ 50 Realizer		125,000 €
Shot peener Comco		13,000 €
Platinum	26,500 €	75.000 €
Invested Capital	201,340 €	235.00 €

It is also true that for casting there is a wide range of machinery available and this could lead to a reduced capital investment while for 3D printing, the capital investment that has been calculated is the minimum one needs to be able to take advantage of this technique. In casting however, the invested capital is mostly needed to buy machinery, while in SLM™ the biggest part of the capital is invested to buy the precious alloy. This is a disadvantage for casting in case the company as to be sold since the sale of precious metal is easier and the return is higher compared to resell used machinery.
However, as mentioned before, the costs of the plants necessary for the correct functioning of casting machinery were not considered. This refers to an electric plant that is more complex, a hydraulic plant that has to serve each machine with refrigerated water, and an emissions control plant that takes care of the fumes during the burnout cycle of the flasks. Furthermore, it was estimated that for a lost-wax casting plant at least 50 m^2 are needed that at the current Italian market value is about 100,000 €. On the contrary, a 3D printer needs less than 1 m^2.

Environmental Impact of Production

The environmental impact is a parameter that is acquiring more importance in the complete evaluation of a production process. In this case study the impact on the environment was quantified for both techniques through the calculation of the carbon footprint (CF), which refers to the quantity of greenhouse gases (GHG) that are released during production in terms of equivalent CO_2 mass.

The comparison of GHG released was done considering all the phases and materials that are necessary for completion of jewelry. Calculation of the emissions caused by production and disposal of the materials used was done by using the data provided by the EcoInvent2.2 Database, while GHG data from electric energy usage was retrieved from the Italian Superior Institute for the Environmental Protection and Defense and based on the production of electrical energy for the Italian net[8] (Tables 31 and 32). The greenhouse gases deriving from the extraction of the raw materials and of the construction of the plants and machineries was not taken into consideration.

Table 31 *Kilograms of equivalent CO_2 produced through casting*

Carbon Footprint: Casting	
Production Phase	**kg CO_{2eq}**
Feeders design	0.06
Wax printing	0.4
Support removal	2.5
Tree mounting	0.07
Flask preparation	0.35
Burnout cycle	16.9
Pre melting	8.5
Melting and casting	5.5
Pickling	0.5
Sandblasting	0.15
TOTAL (approx..)	35

Table 32 *Kilograms of equivalent CO_2 produced through SLM™*

Carbon Footprint: SLM™	
Production Phase	**kg CO_{2eq}**
Supports design	0.04
Pre-melting	2.5
Atomization	1.64
Print	11.7
Shot peening	0.08
TOTAL (approx.)	16

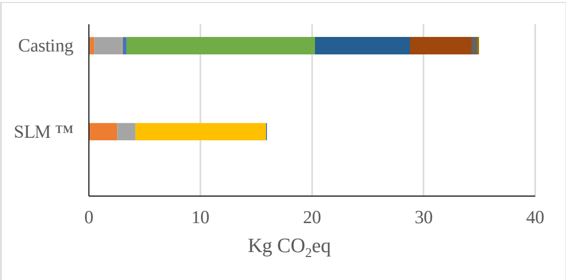


Figure 105 *Kilograms of equivalent CO_2 produced through each technique*

From the results shown in Figure 105, it can be observed that the greenhouse gases released into the environment during the production of the 60 rings using SLM™ is half of those generated through casting. This difference is due to the higher electrical consumption for casting, the gases released during the burn out of the flasks and the usage of materials that have a higher environmental impact.

CONCLUSIONS

From the case study presented here, it can be concluded that from a qualitative point of view the production of platinum jewelry using SLM™ appears superior both in terms of surface macro defects and internal porosity. This data is confirmed through the opinions given by the operators and the number of pieces that had to be corrected using laser, besides the non-conformity determined in three cast pieces.

The production times are slightly slower for SLM™ , but this technique manages to compensate through its efficacy in the production of the common small lots of platinum jewelry with respect to a casting plant. The higher production yield in selective laser melting also limits the necessity of refining, further~~ly~~ providing advantages from a cost point of view.

The total costs are in favor of SLM™ for many of the models produced with only two models appearing advantageous when produced through casting. All this considering that the start-up cost is only slightly higher and has half the environmental impact.

In conclusion, given the collected data, by considering companies that produce only platinum, and with weekly lots of 500 g of raw jewels, the SLM™ technique reveals itself to be superior to casting since it is more suitable for small quantities of platinum jewelry and the more elevated quality the pieces presents compared to casting.

It can be consequently affirmed, as was hypothesized in the work presented at the 2017 Santa Fe Symposium, that production of platinum jewelry is one of the cases in which the SLM™ technique presents an added value over casting.

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