

Review paper**INNOVATION AND OPTIMIZATION OF THE INVESTMENT CASTING OF PRECIOUS ALLOYS**

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Abstract

Various techniques and technologies have been developed and fine-tuned in recent years which have made it possible to improve the investment casting process and extend its field of applicability such as, for example, the application of rapid prototyping, rapid manufacturing, casting simulation and “non-traditional” materials. In the past decades, companies working in the precious metals sector could keep in their collection the same products for a long period, eventually applying minor modifications. Nowadays innovation is considered one of the key point for the success of the production, coupled to an increased attention towards quality and reliability of the product. The present paper deals with an analysis of some of the innovations introduced into the investment casting of precious metals in the recent years, in terms of process analysis, new materials involved for the fabrication and metal alloys.

Keywords: casting, precious metals, computer simulation, thin geometries, bulk metallic glasses

1 Introduction

Investment casting is one of the oldest production processes, dating back over 6000 years ago and already used in jewelry production. It is also commonly known as lost wax casting, since a wax pattern is “invested” (i.e. coated) with a refractory material to form a mold.

The wax pattern is removed by melting (it is “lost”) and then the molten metal poured into the mold, generally made of refractory material (investment). According to the wax and refractory material used, the item is reproduced with very fine details. Good surface finishing and respect of dimensional tolerances constitute the main strengths of this process, together with an overall flexibility in terms of shapes obtainable from a single casting operation, and the freedom from any expensive tooling. However, despite being a very ancient process, the modern technology of investment casting may not necessarily be easy to control, due to the many steps involved. Several metallurgical principles have to be considered and complied, which could make it hard to obtain a good quality product. Moreover, different parameters could vary in terms of technologies, equipment and materials.

A schematic draft of the process is reported in the following **Fig.1**.

The full knowledge of all the aspects related to each step of the investment casting process drafted in Fig.1 are needed to guarantee good results in terms of the final quality of production.

Several studies have been published during the last decades, particularly focusing onto an industrial perspective [1-5] and onto the application of some innovations, especially in terms of

alloys [6,7]. During the last years, however, jewelry industry shifted from the traditional production towards innovation, declined in every aspect: materials, process parameters, geometries and technologies. Innovative technologies, even got from different industrial fields, are more and more applied for production and studies are carried out for their optimization into the jewelry field. In a specific market scenario where the gold and precious metals prices are playing a relevant role into the jewelry design, also the geometry of parts is important; the interest towards the production of hollow parts, light and filigree-like patterns is therefore rising. Product innovation must however proceed with process optimization and quality control. In this frame, the opportunity of “virtual” processing and checking, given by computer simulation, clearly represents an opportunity to improve production efficiency (and quality) and reduce costs.

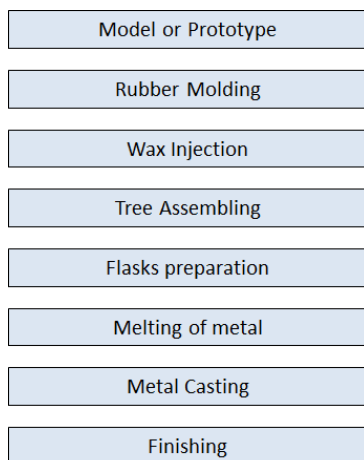


Fig. 1 Common steps of the investment casting process

2 Computer simulation

Several works have been carried out in the past on the use of casting simulation tools to make forecasts on the quality of the objects produced by precision casting. The use of casting simulation software makes it possible to make a priori considerations on several parameters and different assembly configurations, basing on different possible programs [8]. However these tools require an in-depth knowledge of the process and monitoring of the real conditions [9]. It can be noted in the passage to the real conditions that many other factors influence the quality of the finished object and recourse is had to traditional analytical techniques to take account of these.

In particular, all the analytical stages on the finished objects use metallographic analysis, the importance of which is set out in [10].

The assessment of the investment casting process can avail of the help of casting simulation software capable of foreseeing some of the defects that occur on the real objects. Studies have proven the applicability of computerized simulation programs both in the case of silver alloys and gold ones with different carat values [11]. Simulation software provides a valid support for production activity and make it possible to assess the influence of various process parameters without having recourse to a posterior analyses, simulating the form filling and cast

solidification stage. However its use presupposes an in-depth knowledge of the materials used and of the dynamics in play in the process, as highlighted in [12]. It is in fact necessary to prepare a precise geometrical description of the model to be considered and of the assembly configuration, and carry out physic-chemical characterizations of the materials used, both as regards the refractory material and the precious alloy. The simulation using CFD (Computational Fluid Dynamics) often requires a stage for setting and aligning the software with the reality, making measurements with online temperature and filling sensors [9]. The purpose of this stage is to bring together the results of an ideal system, the one considered by the simulation software, with those of a real system which will therefore be affected by different boundary conditions.

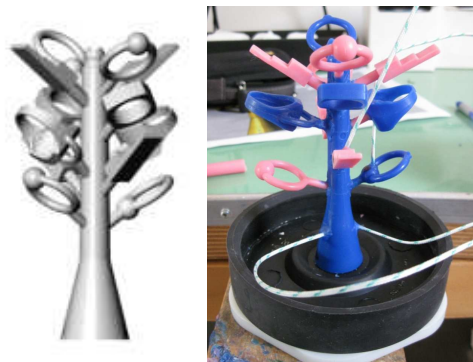


Fig. 2 Examples of a standard tree configuration for the experimental study: CAD drawing (left), and wax model with sensors for acquiring the data during process (right)

The assessment of the results include an analysis of the “real” casting in order to identify any criticalities during the filling stage, for example with the identification the flow soldering zones or any turbulence.

It is therefore possible to draft the following scheme, summarizing the actions for the initial application (and validation) of computer simulation applied to jewelry.

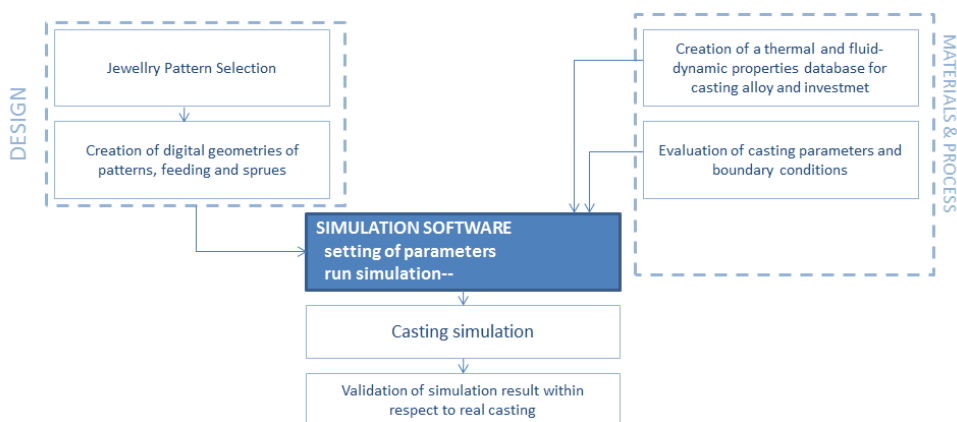


Fig. 3 Scheme of the set of actions to be carried out for the correct use of simulation software into the investment casting

The study of the solidification stage also makes it possible to identify the zones subject shrinkage porosity. With the aid of the software it is possible to go on to analyze sections of particular interest in such a way as to ascertain the real position of the porosity in the object.

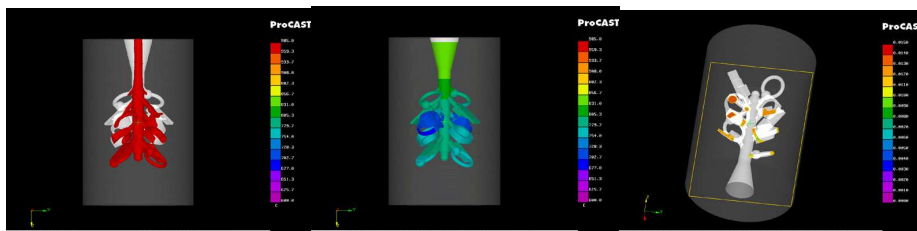


Fig. 4 Examples of frames relating to the filling (left), solidification (center), and porosity analysis (right) stages in the casting simulation software

The casting simulation makes it possible to localize and quantify shrinkage porosity in the various objects with variations in different parameters, and typically assessments are made on the influence of the casting and mould temperatures.

A example is given of the simulation of the sterling silver casting of a standard ring in various mould temperature conditions. It can be seen that with rising temperatures the quantity of shrinkage porosity in the object increases and like it, gradually involves the whole section of the object. These results are in accordance with what has been presented in [13].

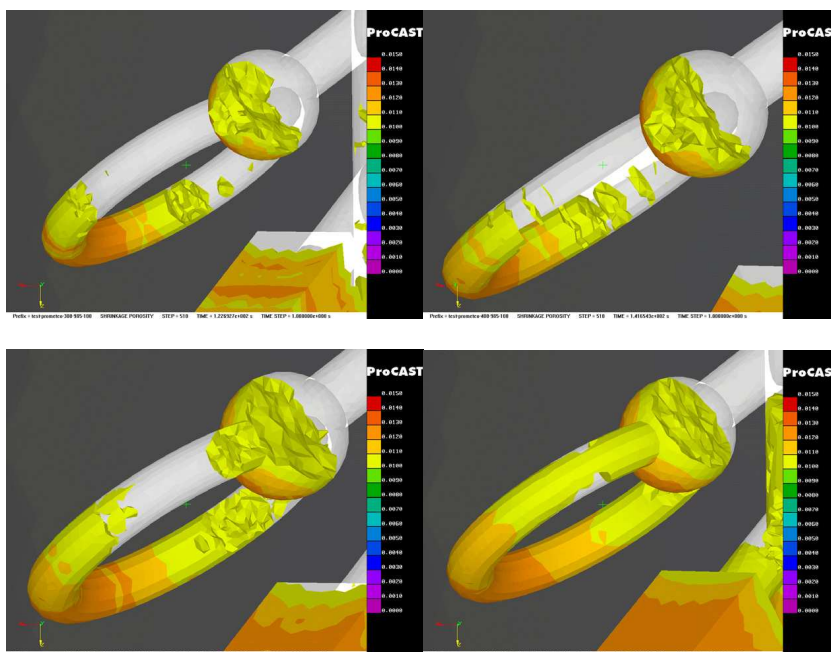


Fig. 5 Analysis of the porosity in the post-process module of the simulation software, detail of a ring with sphere, for trees obtained with a flask temperature at the moment of casting of 300°C (top left), 400°C (top right), 500°C (bottom left) and 600°C (bottom right)

The combined analysis of the two stages, casting and solidification, also makes it possible to assess the effectiveness of particular feed systems, predicting in which way the metal flow will enter the cavity and which zones will be involved last by the filling operation.

It is also possible to make considerations on the thermal stresses which the refractory material receives when the metal is being cast as regards to the capacity of the various mould zones to remove heat. In this way, it is possible to identify zones that are particularly sensitive for the decomposition of the refractory material and therefore for the formation of gas porosity. In particular, it is possible to observe that the presence of objects that are too close together causes overheating of the refractory material which is no longer able to carry out its thermal insulation action.

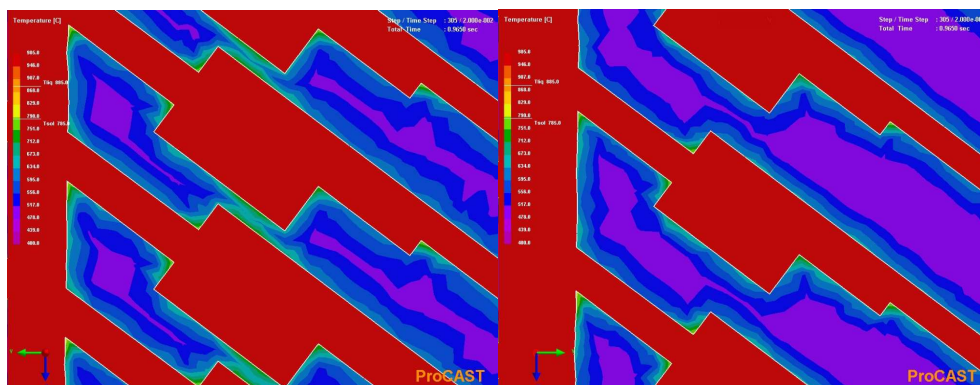


Fig. 6 Thermal stresses of the refractory material depending on the distance between the objects, (left) objects closely mounted, (right) objects correctly spaced.

The casting simulation is therefore a very useful tool for the correct interpretation of the phenomena in progress during the precision casting process. The use of these technologies therefore makes it possible to make an a priori assessment of the various parameters used in terms of the mould and casting temperatures and check the effectiveness of different feed systems. Obviously the software takes an ideal system into consideration and must therefore be integrated with appropriate evaluations of the real process, taking into account what occurs during the tree assembly, investment preparation and metal casting.

3 Casting of thin items

As for jewelry, many other industrial fields had to face the need of production of thin, weight saving sections, not only for economic reasons, but also considering functionality and energy saving contributing to a more favorable strength-to-weight ratio [14-16].

Examples ranging from thin-walled aeronautical turbine blades to automotive components, electronic devices and power production components are perfectly explaining the need for thin, energy and material saving parts.

Many parameters have to be taken into account in order to be able to get constant results in the casting of thin items, starting from the model design and preparation to the final pouring of a metal alloy [17]

As demonstrated in [18,19], design plays a relevant role in the determination of the actual minimum thickness achievable, both in terms of part geometry and in terms of sprue and tree

setting. Different aspects of design (such as the length of the thin section or its proximity to a gate or to heavy sections to drive the metal) have therefore to be examined when going towards thinning. The simple concept of the thinnest section is therefore under-defining the real features of a component, whilst other parameters, such as geometry indexes, could provide a better identification and help in the optimization of the following production steps. The use of the geometrical modulus, usually describing a given geometry in terms of specific surface (surface area/volume) is helping in classifying items according to the tendency towards surface mechanisms (heat transfer, surface reactions..) for a given volume. The first attempt to index parts geometries was carried out by N. Chvorinov in order to understand the solidifying process of a cast part as determined by the molten volume and its cooling surface mutual relation [20].

Once defined the geometry, the following step is related to the production of disposable patterns. When considering the pattern preparation, the main limit is related to the actual possibility of getting a model with thin cross section, either for the mold preparation or for the direct casting of a RP resin.

In case additive manufacturing is adopted for the model production, relevant parameters are related to the minimum layer thickness, material sensibility and working spot size and are changing according to the adopted manufacturing technique. For example, when considering the production of thin items via stereo-litography (SLA), factors both related to construction mechanism (laser power, spot size, scan speed, layer thickness) and to the resin characteristics (cure depth, penetration, exposure) have to be fine tuned [21,22].

Moreover, when considering traditional wax injection into silicone molds, an additional set of parameters have to be taken into account, in order to obtain the wax pattern related to wax thermo-physical and rheological properties and to mold thermal characteristics [23]. In investment casting, waxes are commonly complex mixtures of natural or synthetic hydrocarbons of a wide variety of molecular weights and their thermo-physical properties are usually characterized in terms of volume shrinkage and viscosity [24].

Once demonstrated the possibility to obtain the disposable model, casting parameters have to be taken into account. Traditionally investment casting is recognized as being able to produce intricately shaped components in a wide range of metals, with high degree of detail reproducibility. The possibility of getting thin sections with this technique is function of a wide range of parameters, mainly related to the fluidity of the alloy and to its ability to flow in the mold.

Fluidity is governing the molds filling and sharpness of cast details. Physicists define fluidity to be the inverse of viscosity. Metallurgists, on the other hand, refer to fluidity as the ability of a molten metal to flow and fill a channel or cavity. In foundry and casting industry, fluidity indicates the distance covered by liquid metal in a channel of fixed geometry before solidifying, resulting to be not only a matter of flow behavior but also depending on the ability of flowing and filling the mold. Therefore in this latter case a more complex scenario is taken into account, where many parameters such as heat transfer and roughness play a relevant role [25].

Other parameters to be considered are the temperatures of both mold and metal, alloy selection, feeding system, and casting process.

It is therefore evident that, when trying to identify the key points for the production of filigree objects, a very complex scenario is depicted with several mutual inter-dependencies.

It is extremely difficult to identify the current state of the art of filigrees in terms of resin and of castability. Generally speaking the lower section limit considering investment casting is set to be 0.3 mm but no information regarding the geometry modulus of parts are reported.

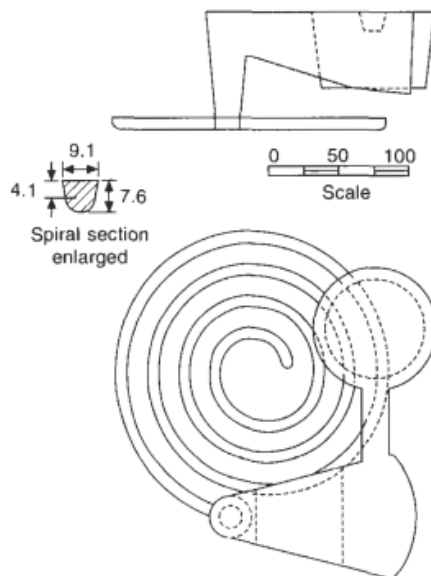


Fig. 7 Foundry Fluidity test [25]

As for stereolithography, since more than one technique and material can be used, it is far more complicated to set the current limits. For particularly complex and thin objects, building parameters may need to be optimized especially not to damage the growing structure.

The building resin is a directly castable product, highly resistant and self-supporting, thus reducing the need of support structures.

As pointed out in [26,27], different parameters can influence the final result of a casting trial, might that be related to feeding systems, process parameters or use of proper materials.

However, when direct casting RP resin, other aspects have to be also considered, such as part cleaning, investment choice, ratio between water and refractory powder in the preparation of the investment (w/p ratio), burn-out cycle. Generally speaking, thermo-set materials, such as usually RP resins, do not melt like waxes during dewaxing and burn-out but they partially soften and burn. This is creating a reactive environment, usually aggressive towards investment materials. The interaction between resin and investment is enhanced by several factors such as burn-out cycle lasting, w/p ratio and part geometry index.

Light filigree-like patterns are characterized by a high specific area, as indicated by the high geometry index value, and therefore may show a higher affinity towards interface reaction with the investment. Moreover, thin and intricate parts, require higher w/p ratio when investing, due to the need of copying fine details and filling small cavities. Feeding a thin part, without almost no thick sections is a demanding and critical task. In fact, this kind of geometry doesn't allow to play with feeding placement or diameter. Different feeding systems may also be adapted, eventually optimized with the help of fluid-dynamic software [28]. When direct casting resins, feeding system is playing a relevant role not only in terms of metal flow but also to guarantee proper ventilation through the cavity and enhance the resin burn-out. Therefore the influence of the presence of casting reservoirs also needs to be considered, playing the role of metal and heat reservoir and of gas trap [29,30].

The following images show an example of filigree object designed, prototyped in castable resin (left figure) and cast in sterling silver by means of centrifugal casting [31].

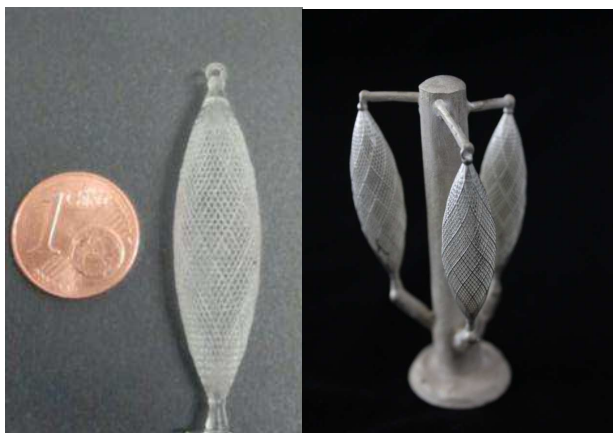


Fig. 8 SL resin pattern net-pendant (left) and as cast tree in silver alloy (right).

Casting thin is only one point of a complex process where many different parameters are involved.

The demonstrated feasibility of extremely hollow thin-walled patterns by means of directly castable RP resins and properly optimized preparation and casting processes represent one possible strategy of a new approach towards “modern” jewelry.

4 Bulk Metallic Glasses

When conventional metal alloys are cooled from their molten state, atoms will quickly rearrange themselves into ordered lattice spaces and quickly crystallize. This crystallization process could be completely avoided, as discovered by Duwez, in 1960, for the Gold-Silicon system [32], which however requested relatively high critical cooling rates (of about 10^6 to 10^8 K/s) to form the amorphous solid.

Bypassing crystallization during cooling of the melt does not only mean that an amorphous phase is formed, but also that crystallization shrinkage is not taking place.

The following figure reports a simplified relationship between volume and temperature during the cooling of BMG-forming liquid and crystals-forming liquid.

Upon cooling, molten metal would typically undergo an abrupt freezing, followed by a 4–9% drop in volume (ΔV) as denoted by the length of a solid vertical line drop. BMG-forming liquid has incredible stability against crystallization and will not crystallize upon cooling. The dash line represents a cooling pathway for a BMG liquid that shrinks in volume and remains in a liquid state even after the temperature drops below T_m into a deeply under-cooled liquid region. Right around T_g , liquid metal freezes and becomes solid without much change in volume.

The lack of crystallization shrinkage leads to a significant reduction of shrinkage-related casting defects like shrinkage porosity. This also means that only minor dimensional discrepancies between casting products and mold geometries are present, and filigree surface patterns are accurately reproduced on the surface of the cast product. Near net-shape casting can therefore be applied.

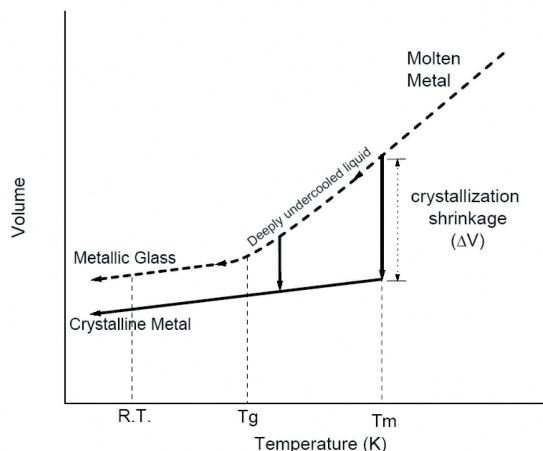


Fig. 9 Volume change at solidification for a „crystalline“ alloy and for a metallic glass

Most bulk metallic glasses are found at eutectic or near-eutectic compositions [33,34].

As for what concerns precious metallic glasses, typical compositions are represented by a platinum based alloy ($\text{Pt}_{85.24}\text{Cu}_{7.1}\text{Ni}_{2.36}\text{P}_{5.3}$), which can be cast at 600–800°C compared to more than 1800°C for conventional Pt alloys [35] and a gold based alloy ($\text{Au}_{76.26}\text{Ag}_{4.69}\text{Pd}_{1.93}\text{Cu}_{13.5}\text{Si}_{3.62}$), which is showing a glass transition T_g of approx. 130°C and a crystallization temperature T_x of 186°C. The following table reports the main characteristics of the two aforementioned alloys and, for comparison, those of commercial crystalline alloys [35].

Table 1 Main properties of BMG and crystalline alloys based on Au and Pt systems

	Au 18K BMG	Au 18K crystal.	Pt 850 BMG	Pt/Ir, Pt/Co crystal.
Melting temperature	371°C	~1000°C	522°C	~1700°C
Casting temperature	450–600°C	>1100°C	600–800°C	>1800°C
Glass transition temperature	130°C	N/A	235°C	N/A
Yield strength (MPa)	1100	350	1470	420
Vickers hardness (Hv), as-cast	360	100-150	400	110-160
Density (Mg/m^3)	13,7	15,4	15,3	21,5

To cast a completely amorphous BMG alloy, the processing may be similar to casting conventional precious metal alloys. However, the cooling path during solidification from casting must not intersect the crystallization “nose” as shown by the dark blue curve in the following figure 10. Intersection into the crystallization zone would cause the BMG to crystallize partially or fully.

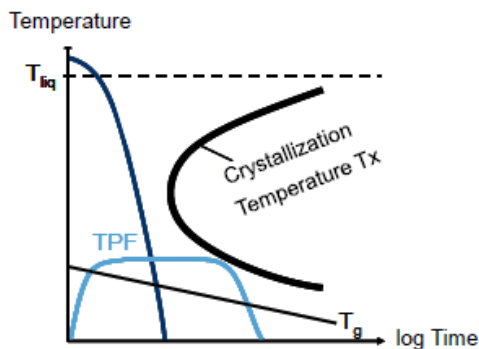


Fig. 10 Schematic TTT diagram with crystallization nose and typical temperature profiles for casting and thermoplastic forming (TPF)

The critical cooling rate for Au based BMG is approximately 100°C per second, while Pt based BMG require 8–15°C per second.

This results in one possible limitation related to the use of the aforementioned alloys into traditional casting processes: the critical casting thickness. It is reported to be equal to 5mm for gold alloys [35] and of about 20 mm for Pt alloys. Higher thickness result in a progressively increasing degree of crystallinity of the final product.

Another alternative way to get the final product can however be by means of thermoplastic forming (azure line in figure 10) for processing the material.

In this case there are two separate processes involved. Firstly the material has to be shaped in a „glassy feedstock like shape“; secondly the glassy feedstock must undergo thermoplastic processing (without intersecting the crystallization curve). Feedstock material could be made in different shapes and sizes based on the requirement of the final net-shape forming stage. Pellets or granules can be produced by jet-nozzle quenching into water or other liquid [36, 37].

Despite being relatively new, the use of BMG for the production of jewelry has already proven its potentialities, especially in terms of the final mechanical characteristics which can be obtained. However, despite higher hardness and eventually easier processability, the full exploitation of BMG for jewelry production still needs a final validation which can be obtained only through the support of industries.

5 Conclusions

Several opportunities are possible, both in terms of materials and processes, to improve production quality, efficiency and properties of precious metals products.

Casting does not have to be considered a simple process or the final point of production, but the starting point of a complex process where many different parameters are involved.

According to the opportunities given by the use of new (most of the times to be intended in terms of application to the jewelry sector) materials/devices, several properties/parameters/design issues have to be “engineered” or “re-engineered” in order to get consistent results both in terms of production and wear-ability.

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