QUALITY LEVEL IMPROVEMENT IN INVESTMENT CASTING: ARE LAST GENERATION CASTING MACHINES THE ONLY SOLUTION?

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ABSTRACT

Melting and casting can be carried out in high technology equipment, but they are only the culminant point in the metallurgical performance of the investment casting process: melting and casting are of crucial importance even in the unfavorable sense, but they cannot correct or wipe out the effect of metallurgical errors that have been made in preceding phases.

Some aspects of the phases preceding melting and casting, like mold optimisation and flask treatment, are also considered, because too frequently these operations receive insufficient attention or are considered separately from the whole process. Then it is discussed how control of the subsequent melting-casting phase, selection of the operating parameters and process data collection, that are possible with the most up-to date machines, can lead to improved product and high productivity in the jewelry factory.

KEYWORDS

Burnout oven temperature homogeneity, burnout process, burnout program, calcium sulphate bonded investment, casting temperature, flask temperature, gas porosity, gold alloys embrittlement, investment casting, investment cracks, silicon addition, casting defects, rubber molds, wax patterns.

Introduction

There are apparently obvious topics that should be repeated ad nauseam, hoping to put them into the genetic code of the goldsmith!
One of these topics is not to waste money for buying a new, up to date, melting/casting machine if one is not sure of having a thorough understanding of the whole process of investment casting.
Process understanding does not mean to be able to carry out with closed eyes a set of repetitive operations, but to understand the significant metallurgical factors for each operation, so to avoid unwanted effects on the quality of the finished product.
Even if completely automated, a melting/casting machine, can only melt and cast. But melting and casting are only the two final steps of the process. The machine cannot be responsible of errors or negligence in the preceding steps, which can dramatically affect the end result. However if the preceding steps have been accurately carried out, a last generation machine can give the best guarantee of a final result complying with the required characteristics.
To say a paradox, today such high perfection machines are available on the market, that are able to perfectly and endlessly repeat the defects resulting from a systematic metallurgical error made by the goldsmith!

In this paper I will discuss only some steps of the investment casting process, that have been particularly studied in POMELLATO during the past year. One year ago the equipment of POMELLATO for investment casting has been modernized, after careful work aiming to get a better understanding of the metallurgical bases of investment casting.

The investment casting process up to casting can be subdivided into ten steps (1):

1 - design
2 - making the master model
3 - making the mold
4 - production of the wax patterns
5 - assembling the tree
6 - preparation of the investment mold

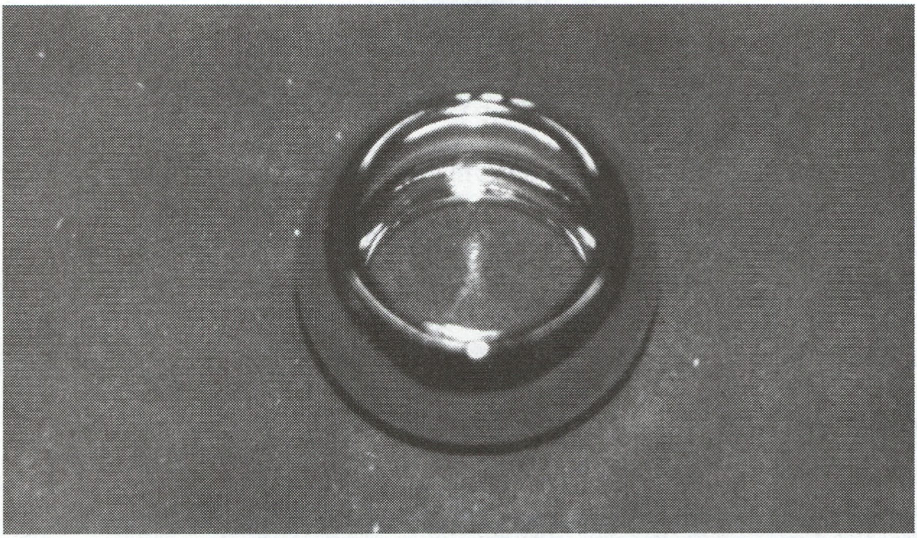

Figure 1 – Ring with a marked undercut

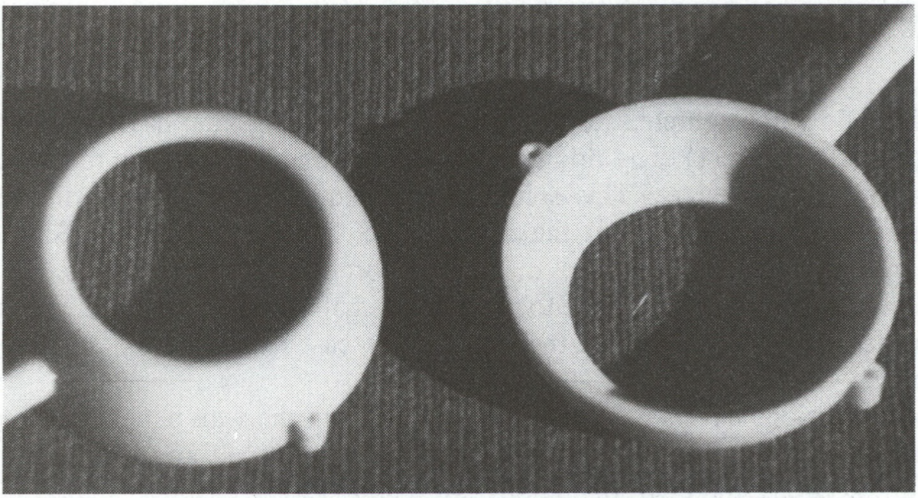

Figure 2 – Wax pattern of the ring shown in figure 1, that has been produced in two halves. Notice the locating protrusions for assembling the halves of the pattern

7 - dewaxing
8 - burnout
9 - melting
10 - casting.

I will discuss the following steps: making the mold, burnout, melting and casting.
The first basic rule that should always be remembered is to carry out all operations in the simplest way: there are so many possibilities of making errors, that there is no reason of increasing the probability of errors by making the operations more complicate.

Making the mold

In the past Symposia it has often been said that the quality of investment cast jewelry principally depends on the quality of the wax patterns (2), that in its turn depends on the quality of the mold. Then the availability of a skilled moldmaker is a basic condition for a good product. A skilled moldmaker should design the mold in such a way to make the subsequent manufacturing steps as simple as possible: that is, he should have what has been defined a "symbiotic relationship with the caster" (3).

The following example refers to a simple item, a ring, that has a marked undercut (Figure 1). The original solution has been to produce the wax pattern in two halves. This solution has been adopted because of the short time available to put the new product line on the market. Since then this practice has been mantained for a long time (Figure 2). Subsequently, it was possible to join the two halves of the wax pattern or to cast them separately and then to join the cast halves with a suitable solder.
Both solutions have some disadvantages. Joining the wax patterns is the simplest way, but it is difficult to achieve a good result and longer and more accurate finishing operations are required after casting. Soldering the cast halves is easier, but in all cases a long time is required for finishing. There is the possibility of porosity formation in the soldering

zone and with the use a color mismatching could appear between the base alloy and the solder.
The solution for these problems has been found by building a more complex mold, where the inner part of the mold (corresponding to the undercut) can be disassembled and removed. In this way the wax pattern can be produced as a single piece, finishing labor can be minimized and major cost and quality level benefits can be achieved (Figure 3).
The preparation of a mold of this type requires high skill from the moldmaker, who should cut the rubber in such a way that the separation lines between the different parts do not interfere with the main surfaces. Moreover he should take care not to damage the master model when cutting the mold.

The danger of damaging the master model is higher when it has a large number of setting posts. In these cases another technique, that avoids mold cutting, is used by POMELLATO. In this way mold preparation is much easier.
Before vulcanizing, the mold is assembled in the conventional way, with several rubber layers. When half the mold has been filled, small cubes (about 5x5x5 mm) are cut from a vulcanized rubber piece (for example an old mold). The cubes will act like locks for assembling the finished and vulcanized mold halves, and are located on the outer perimeter of the mid section of the mold (Figure 4). The upper free surface of this assembly is dusted with talc powder or sprayed with silicone oil or is covered with a thin teflon film. Then another layer of rubber is laid in the zone delimited by the rubber cubes and it is also dusted in the same way. The master model is laid down on this layer and the operation is continued in a mirror-like way (with the exception of the rubber cubes), until the mold is completed.
Then the mold is vulcanized. After vulcanizing, the mold can be opened with the simple pressure of the fingers, and the use of a scalpel is not required.
As a result, we obtain a mold that, in our case, is composed of four parts: the main body, which includes also the small rubber cubes, is formed by two parts and there are also two inner parts, that form the true mold.

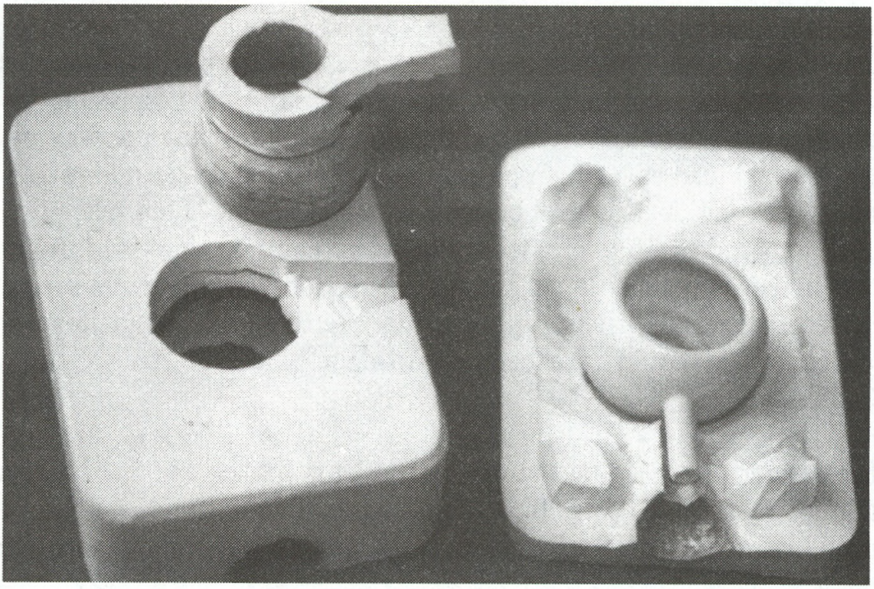

Figure 3 – Mold for producing the wax pattern of the ring shown in figure 1 as a single piece

Figure 4 – Example of the mold used by POMELLATO for producing jewelry pieces with many setting posts: assembling the mold

The inner parts are thin and flexible and can be easily separated from the wax patterns without damaging them (Figure 5).
However this technique can give problems if a skilled moldmaker is not available. If the separation zone has not been designed correctly, the separation line may be imperfect, and later difficult finishing operations will be necessary.
In any case it should be pointed out that, with an accurate design and with the materials that are now available (like vulcanizable rubber, silicone rubber etc.), it should always be possible to build a perfect mold, that is the first requirement for producing good quality castings.

Burnout

Presently, everybody should know that burnout is very important and that in this manufacturing step it is possible to do unrecoverable damage to the refractory mold, when calcium sulphate bonded investment is used (4). The investment can also be damaged during casting, e.g., if it is not possible to monitor flask temperature at the moment of casting.
Usually one relies on the temperature of the burnout oven, and assumes that it is correct and that flask temperature is homogeneous and stabilized at the temperature of the oven.
But are these assumptions true? Moreover, can we be sure that temperature is homogeneous in the whole oven work chamber?
Measurements that have been carried out in average size industrial ovens, designed to treat 15 to 20 flasks, showed that temperature differences up to 70°C (126°F) could be present between the different zones of the oven chamber.
Moreover the defects that have been observed in specific zones of the flasks indicated that these zones have been heated to too high a temperature, or that heating has been too fast, because they have been submitted to direct heating by radiation from the resistors of the oven.
It has been verified that the flask zones with defective castings were directly facing the resistors in the burnout oven.

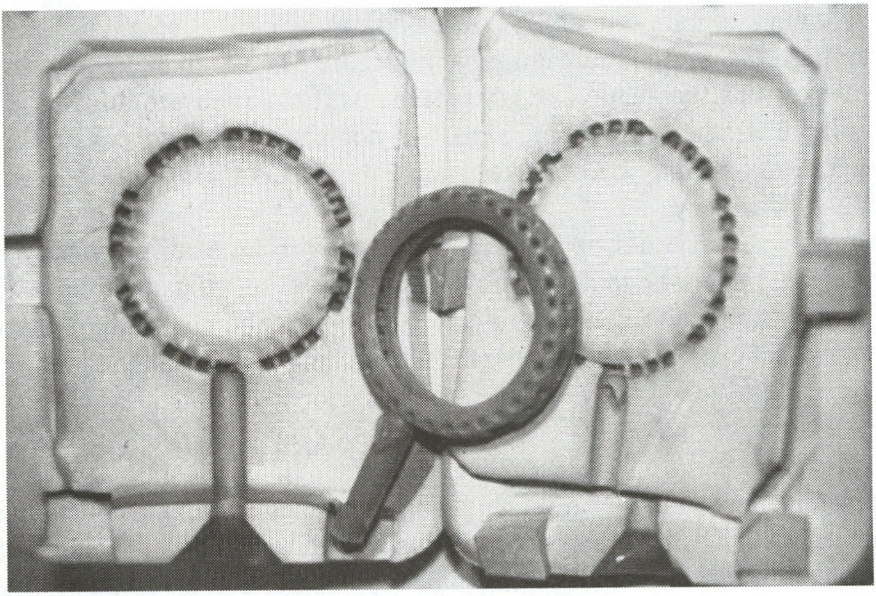

Figure 5 – The same mold of figure 4, finished

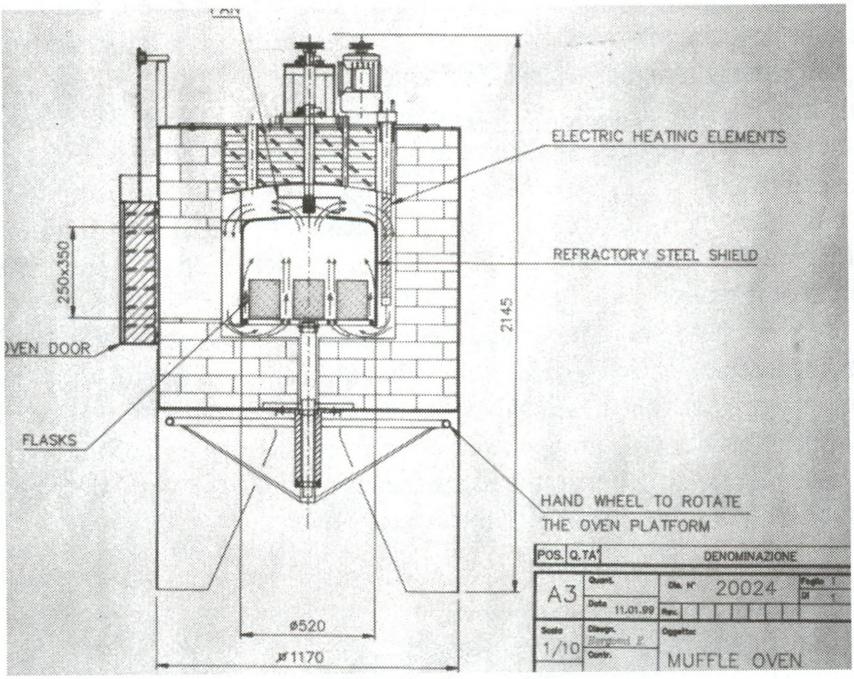

Figure 6 – Burnout oven used by POMELLATO

Consequently, POMELLATO's attention turned to the characteristics required for a burnout oven that could be able to guarantee an accurately controlled burnout treatment.
It has been realized that, in a midium size oven, temperature homogeneity can be guaranteed only by forced air circulation. Moreover a refractory steel heat shield should be placed in the oven chamber, to avoid direct heating of the flasks by radiation from the resistors.
Then a specialized firm has been commissioned to build an oven with a superalloy fan on the upper side that circulates air from the oven chamber to the resistors, that are placed behind a refractory steel shield, and back to the lower side of the oven chamber (Figure 6).
In this way, temperature homogeneity is guaranteed and combustion of wax residues is made more easy, thanks to the forced air circulation.
The oven is equipped with a programming regulator of the temperature cycle and with a double temperature monitoring system with two termocouples, that are respectively placed in the work chamber and near the resistors.
The temperature can be recorded with a 6 channels chart recorder, that allows to record the burnout cycles. This recorder enabled also to record the temperature evolution in the flasks, during the burnout cycle. For this purpose, some flasks have been equipped with five thermocouples, that have been placed in different parts of the flask. The thermocouples were placed in the following flask zones, respectively (Figure 7):

- three thermocouples halfway between the top and the bottom of the flask, one near the main sprue, one near the outer wall and one at half-radius of the flask.
- one thermocouple at half radius of the flask, 2 cm (about 3/4") below the sprue button.
- one thermocouple at half radius of the flask, 2.5 cm above the flask bottom.

With this experiment we have repeated in an industrial oven and in a simplified way the experiments that have been carried out previously by Eddie Bell in a laboratory oven (4, 5, 6).

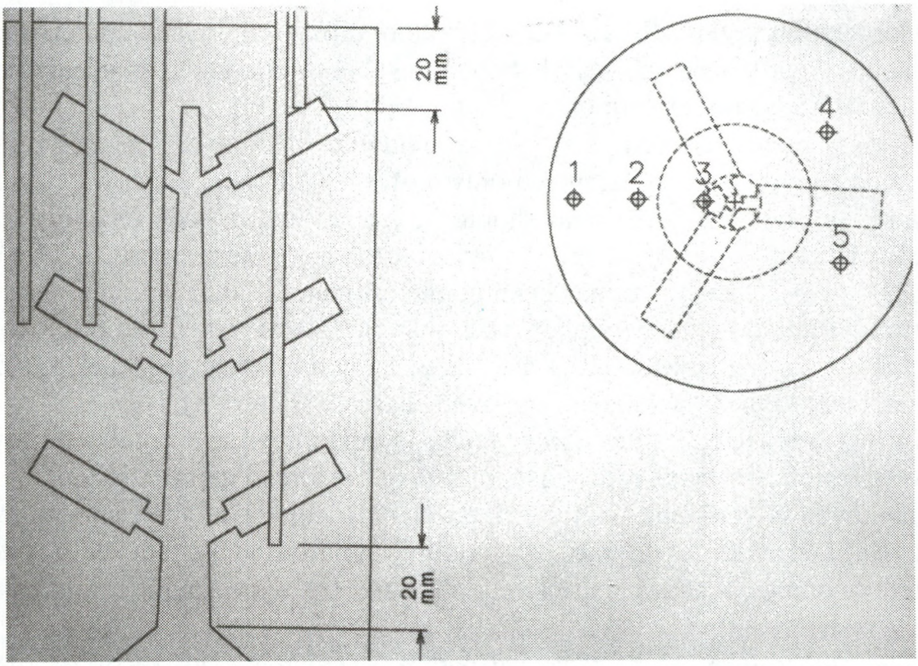

Figure 7 – Schematic representation of thermocouples positioning foı measuring investment temperature in the flask

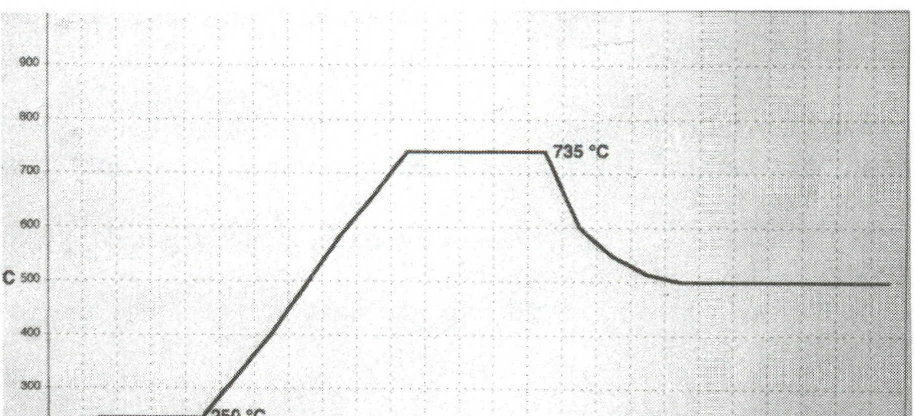

Figure 8 – Schematic representation of the burnout cycle

Figure 8 gives a schematic representation of the burnout cycle usually carried out for the calcium sulphate bonded investment: this cycle is recommended by the producer of the investment powder.
The hot flasks coming from steam dewaxing are introduced in the burnout oven preheated to 150°C (302°F).
When the oven temperature reaches 250°C (482°F), the temperature near the outer wall of the flask (thermocouple nr. 1) is about 40°C (72°F) lower. There is no significant difference among the other thermocouples, that give investment temperature around the cavity left by the wax tree. The temperature measured by these thermocouples is about 80°C (144°F) lower than oven temperature.
Flask temperature takes about 1 hour and half to reach equilibrium with oven temperature.
When oven temperature starts rising again, investment temperature in the inner part of the flask (thermocouples nr. 2, 3, 4 and 5) shows a delay of about half hour. Therefore the investment is held at 250°C (482°F) for about 2 hours, in comparison with a 3 hours holding time of the oven.
When oven temperature reaches 735°C (1355°F), the temperature near the outer wall of the flask is about 20°C (36°F) lower. The temperatures measured by the other thermocouples are about 80°C (144°F) lower than the oven temperature.
Equilibrium with oven temperature has been reached after 1 hour and half.
When the oven temperature starts decreasing, flask temperature (inner part of the flask) shows a half hour delay. Therefore the investment is held at 735°C (1355°F) for about 3 hours, in comparison with a 4 hours holding time of the oven.
During oven temperature decrease, thermocouple nr. 1 temperature is 20°C (36°F) and inner flask temperature is 40°C (72°F) higher than oven temperature. After 1 hour holding time at 500°C (932°F) the temperature of the whole flask can be considered in equilibrium with oven temperature.

Burnout oven reliability and accurate knowledge of the flask response to the programmed temperature cycle are of fundamental importance to obtain good and consistent results. We should remember that we work in

a "temperature system" where flask temperature (controlled by the burnout oven) and liquid metal temperature (controlled by the casting equipment) are strictly related and should be selected as a function of the alloy type and of the shape, size and thickness of the items to cast. Quite often a 10 to 20°C (18-36°F) error in metal or flask temperature can be crucial for obtaining the desired result.
As it has already been said in other occasions, for the burnout cycle it is also important to follow the recommendations of the producer of the investment powder. Investment powders of the same type, but produced by different companies, can have a different content of some components and it can strongly affect their behavior during the burnout cycle.

As an example, in figure 9 some defective castings are shown that show fins that formed because the flask cracked during the burnout cycle. In this case a new brand of investment powder had been tried and the producer had not given directions for the use of his product. Therefore the usual burnout cycle has been followed, that included a 3 hours holding time at 250°C at the starting of the cycle. Later on it has been known that the new investment required a holding time of 3 hours at 180°C. The rapid rise of the temperature up to 250°C did not allow the structural transformations, that are characteristic of the particular components of this type of investment, to take place slowly enough to avoid build up of internal stresses. Consequently a nearly continuous net of cracks developed in the flasks and gave rise to the observed defects.

Melting and casting

Even if all preceding steps have been accurately carried out and even if the most sophisticated melting/casting machine is used, there are still very good probabilities of producing defective castings, if the metallurgical properties of the alloys we are using are not sufficiently known.
I will give only two examples, taken from the problems that recently affected the production process of POMELLATO.

The first problem originated from the use, very common today, of silicon containing master alloys for the production of 18 ct gold alloys for investment casting.
Silicon should improve form filling performance and lower oxidation of the cast tree (7).
Actually, after removing the investment, the cast trees are very beautiful, with a shiny, non oxidized surface, and usually it influences very favourably the imagination of the goldsmith, who believes to see a perfect product!
However silicon can also have two adverse effects: it increases grain size and it tends to segregate at the grain boundaries. These effects can make the alloy very brittle (8, 9).
When silicon containing alloys are used, if one tries to resize a ring, or if the ring is heated for some manufacturing operation, very frequently the alloy shows brittleness and forms nets of cracks that make it unusable (Figure 10). Metallographic examination of rings that have shown this kind of behavior has evidenced that anomalous grain growth and a marked segregation of silicon at the grain boundaries were present. In these alloys silicon content did not exceed 250 ppm, that, according to technical literature (10), is the maximum allowed concentration in 18 ct gold alloys.
This experience leads us to share the opinion of Dr Ott, who maintains that addition of silicon to gold alloys is dangerous and that silicon concentration is difficult to control. The results may be interesting, but there is always the risk of generating defects that cannot be repaired, at least in the 18 ct alloy we use (75.15% Au - 15.75% Ag - 9.1% Cu).

The second problem is related to the behavior of different alloys in regard to gas porosity, originating from the decomposition of calcium sulphate binder that is contained in the investment.
In this case the same jewelry piece was produced with a 18 ct yellow gold (75.15% Au - 15.75% Ag - 9.1% Cu) or with a 18 ct white gold alloy (75.15% Au - 13.4% Cu - 4.15% Zn - 7.3% Ni). Both alloys have nearly identical melting range, so the same casting temperature (1080°C = 1976°F) and the same flask temperature (500°C = 932°F) have been used for casting rather thick rings.

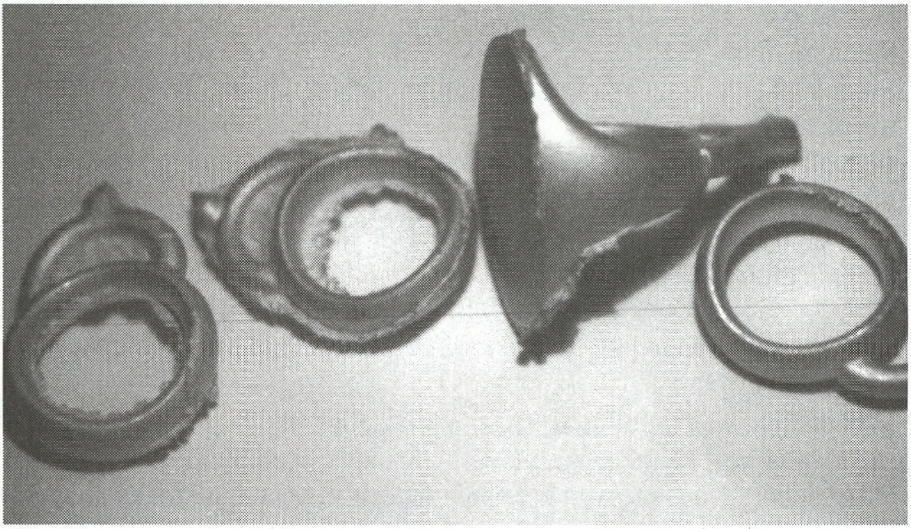

Figure 9 – Fins on some rings, that have been originated by cracked investment

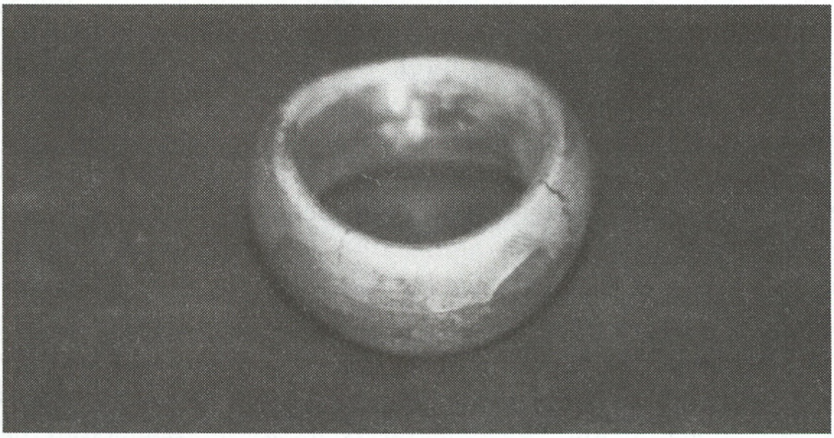

Figure 10 – Ring embrittled by segregation of a silicon eutectic. Cracks formed during resizing

The yellow gold rings were perfect, but the white gold rings where affected by a diffuse porosity, that appeared to be shrinkage porosity.
Metallographic examination of the cross section of the rings has confirmed that porosity is absent from the yellow gold rings. On the contrary, a nearly continuous dendritic structure has been observed on the outer surface of the white gold rings, and, cavities were present on the inner surface, that appeared to be due to shrinkage. Moreover observation of the cross section showed that spherical cavities, typical of gas porosity, were also present.
Therefore more sophisticated observations have been carried out with the ESCA technique. These observations evidenced that a very thin layer of zinc oxide and of copper oxide (probably CuO) with nickel oxide was present on the dendritic branches: these compounds promote the decomposition of calcium sulphate.
As a result, the defect we have observed is similar to case 10 of the WGC Handbook on Casting and Other Defects (9). The cast metal starts solidifying with dendritic crystal growth. If the temperatures of the flask/melt system are too high or if particular compounds are present which catalize the decomposition of calcium sulphate, sulphur dioxide gas is generated, that pushes back the liquid metal still present among the dendritic branches of the growing solid. If the gate is still in the liquid state, the liquid metal can be pushed back out of the mold in the direction of the sprue button, leaving behind a set of dendritic cavities, that are much more numerous than those usually correlated with shrinkage porosity. In addition, the usual gas porosity is also present.
Since a very reliable burnout oven and a melting/casting machine guaranteeing a perfect temperature control were available, our first operation has been to keep the same casting temperature (1080°C = 1976°F) and to lower the flask temperature for the white gold alloy. In the initial tests, the flask temperature has been set at 400°C (752°F). As a result, the defects have been strongly decreased, but they were not fully eliminated.
Our second operation has been a further lowering of flask temperature, that has been brought to 380-390°C (716-734°F), and at the same time we have decreased the gate diameter, near the joint with the cast item. The gate diameter has been brought from 3 to 1,5 mm (from about 1/8"

to about 1/6") for a length of 2mm (5/64") near the joint with the cavity of the mold (Figure 11). In this way the last part of the gate behaves like a one-way valve: when the mold cavity has been filled, the narrow part of the gate solidifies and the liquid metal cannot be pushed back by the sulphur dioxide gas. These additional adjustements enabled to obtain a further improvement of product quality.

From the above, we can realize that the investment casting process is not a simple sequence of standardized operations. Each operation is tighly connected with the antecedent ones. Each operation requires metallurgical understanding and it should be carried out in accord with correct metallurgical principles.

Characteristics and advantages of new investment casting equipment

Actually, after many efforts aiming to improve the understanding of the metallurgical aspects of investment casting, it has been realized that the control of several variables affecting the quality level was insufficient, because of the poor reliability of the available process control systems.
Consequently POMELLATO has been obliged to make a change, to attain the very high quality level, that is expected for the produced jewelry type, in a more consistent way.

Since about one year, POMELLATO has replaced the melting/casting machine and the burnout oven with new equipments.

As already said, a burnout oven built and perfected on the ground of the requirements and of the experience of POMELLATO, and a completely automated static melting/casting machine, equipped with a POV (Pressure Over Vacuum) system have ben selected.
Melting is carried out by means of low frequency induction heating, that can guarantee an effective stirring of the molten alloy.
The real time temperature monitoring and control system of the melting/casting machine is fully reliable. Moreover the machine is also equipped with an optical pyrometer, for measuring flask temperature

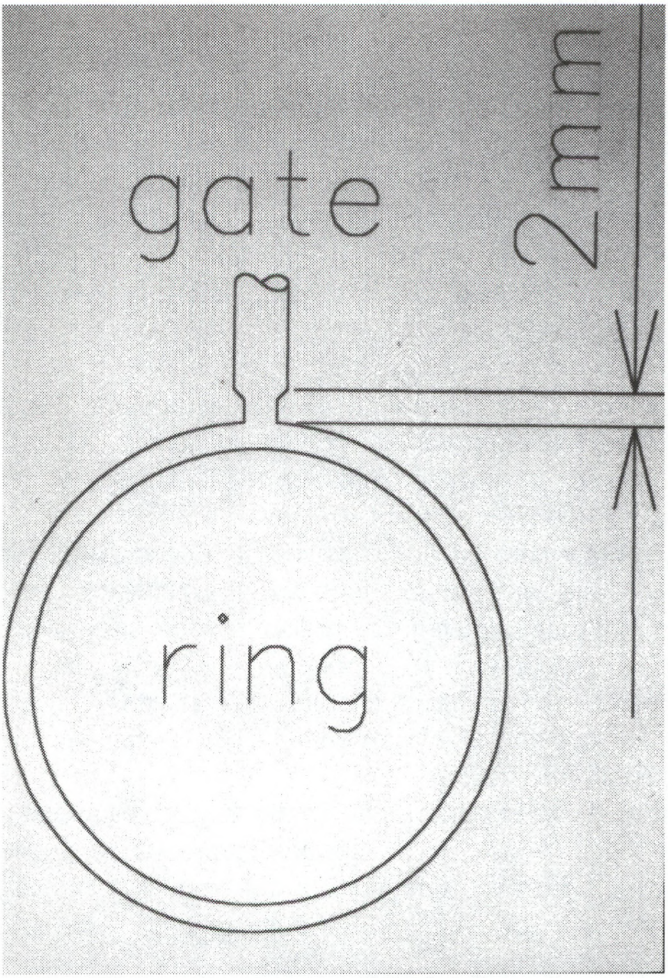

Figure 11 – Gate narrowing to prevent defects due to the calcium sulphate decomposition

before casting (Figure 12), and it is interfaced to a PC to record all operating parameters.

Alloy graining is possible. If the alloy used for investment casting comes in the form of casting grain with optimized size and uniformity, it is possible to obtain a better control of temperature and to avoid detrimental melt overheating. In this way, loss of alloy elements by evaporation can be minimized and also the formation of some kinds of defects that can be ascribed to a too high casting temperature can be reduced to a minimum.

Since one year, we are working with the new equipment. Thanks to the metallurgical understanding we had previously gained, we can say that we have achieved a marked improvement of quality level and, particularly, a very consistent quality.
This new equipment enabled us to reduce the time required for melting and casting. In this way productivity can be increased, but also the operator has more time to plan his work and to verify more accurately all details affecting product quality.
Recording operation parameters enables to create a database that is continuously updated and enables to obtain a better understanding of any problem that could intervene.
Measurement of flask temperature before casting, gives added reliability to the process: if the optical pyrometer has been correctly calibrated and if the correlation with oven temperature has been determined, one can immediately know if something in the burnout cycle went wrong. In a year of work, caratage uniformity problems have never arisen. This fact by itself allows to pay for the new equipment in a relatively short time.

A few defects still occur, and probably they will occur also in the future. These defects could be defined as "phisiological defects" and can be ascribed mainly to the difficulty of manufacturing specific jewelry pieces and also to the frequent necessity of compromises, because of production requirements. Defects of this kind can be kept under control and can be minimized with modern equipment. Probably, it will never be possible to eliminate them completely: indeed the oldest process used by

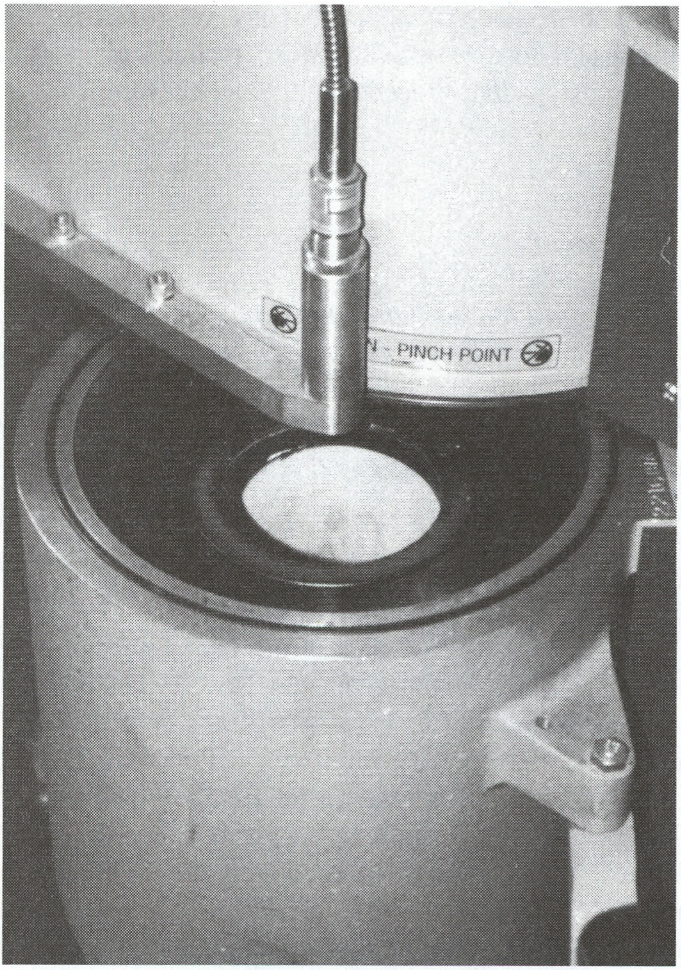

Figure 12 – The flask temperature measurement by optical pyrometry in the casting machine

man for producing jewelry was and is also today a process of artistry. Unlike the large scale production of mechanical components, the complex shape of jewelry items that are produced in limited number does not consent to use very advanced technology, particularly in the manufacturing steps that precede melting and casting.

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References

1 - V. Faccenda - "Advances in Investment Casting Machine Technology" - *Gold Technology* n° 20 - Nov. 1996 - p. 3.
2 – T.L. Donohue and H.F. Frye – "Process control: power, value and advancement for the jewelry industry" – Proceedings of the Santa Fe Symposium on Jewelry Manufacturing Technology 1998 – p. 179.
3 - A.M. Schaler - "Design and Casting: the Tale of a Symbiotic Relationship" - Proceedings of the Santa Fe Symposium on Jewelry Manufacturing Technology 1997 - p. 357.
4 - E. Bell - "Wax Elimination, Burnout and the Mold's Effect on Porosity in Castings" - *Gold Technology* n° 11 - Nov. 1993 - p. 21.
5 - E. Bell - "Heating and Cooling Characteristics of Investment Molds" - Proceedings of the Santa Fe Symposium on Jewelry Manufacturing Technology 1988 - p. 259.
6 - E. Bell - "Heating and Cooling Characteristics of Investment Molds - Research Update" - Proceedings of the Santa Fe Symposium on Jewelry Manufacturing Technology 1989 - p. 357.

7 - G. Normandeau - "The Effect of Various Additives on the Performance of an 18 Karat Yellow Gold Investment Casting Alloy" - Proceedings of the Santa Fe Symposium on Jewelry Manufacturing Technology 1996 - p. 83.
8 - D. Ott - "Analysis of Some Common Casting Defects" - *Gold Technology* n° 13 - July 1994 - p. 10.
9 - D. Ott - "Handbook on Casting and Other Defects in Gold Jewellery Manufacture" - Ed. World Gold Council - Nov. 1997 - p. 35.
10 - "G. Normandeau and R. Roeterink - "Metal/Mold Reactions with White Golds" - Proceedings of the Santa Fe Symposium on Jewelry Manufacturing Technology 1997 - p. 245.