Investment casting: Centrifugal or static vacuum assist?

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Introduction

Complete and perfect form filling has certainly been the first requirement perceived by the ancient goldsmith, when he started to use investment casting in his workshop. The same holds true for the present modern factory.

Consequently, we can say that the goldsmith has always striven to find suitable means for forcing the liquid metal in the mould, to fill even complex cavities and to obtain a faithful replica of the model. Obviously, the more this force is effective, the more the shape of the cavities to be filled can be complex and detailed, increasing the goldsmith's freedom to design new jewellery pieces.

Looking at the past, we find evidence of odd solutions that confirm this. One of them is the "manually powered" centrifuge - sling casting, shown in figure 1, where the operator's arm applies the centrifugal force to the flask. Another one is a kind of static pressure casting, where the pressure generated by the steam produced by an application of a potato, figure 2, is used to improve mould filling.

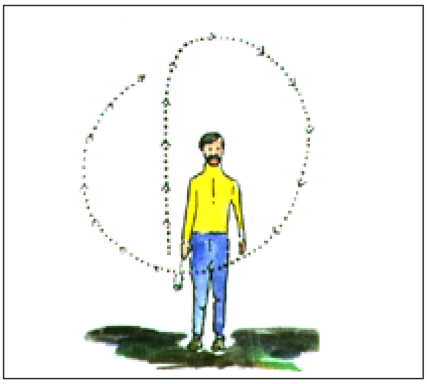
Happily, technology development today makes a wide range of equipment available to the goldsmith, from simple to very sophisticated. But a question is still open: is it better to prefer a centrifuge or a static casting machine? If we consider which is the most widely used kind of equipment, we should answer: the centrifuge.

But we should not forget that the goldsmiths started to use centrifuges only about half century ago. Centrifuges, thanks to centrifugal force, enabled the attainment of better quality castings and came from the field of dentistry, where they have been used for a long time. In this way, the use of investment casting in the field of jewellery manufacture evolved from a mere handicraft technique into an industrial process. Since then, much progress has been made. We will not describe the gradual equipment evolution that has taken place in the past, but rather we will consider equipment presently available on the market, possible future technology evolution and the pros and cons of presently used methods, i.e. centrifuge and static casting.

Equipment technology evolution

Recent research on jewellery production by the investment casting process has emphasised the importance of continuous and accurate temperature monitoring and control. The importance of this parameter has often been overlooked or inattentively considered, not only by the goldsmith, who even today believes that the best temperature control instrument is his own eye (sometimes it really happens!), but even by equipment manufacturers.

Figure 1 - a) Preparation of the flask and of the sling caster; torch melting in the dome-shaped opening at the mouth of the flask.



b) Hand centrifugation by the operator.

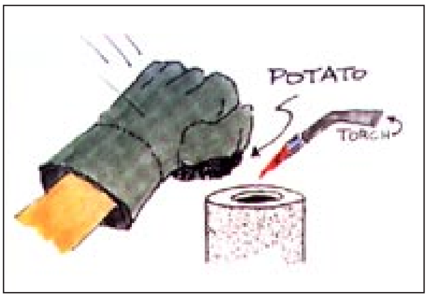


Figure 2 - After melting the metal, half a potato is immediately pressed on the flask, so as to seal its upper part. The steam produced pushes the molten metal into the mould cavity.

Table 1. Statistics on Jewellery Defects (After D.Ott, FEM)

Fabrication Method	**%**
Investment Casting	79
Mechanical metalworking	17
Others	4
Type of Defect	**%**
Porosity	47
Cracks	28
Corrosion	16
Annealing	9

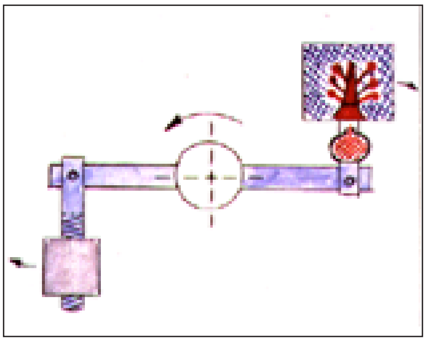


Figure 3 - Sketch of a variable geometry centrifugal casting machine (plan view)

Figure 4 - Detail of a variable geometry centrifugal casting machine with the temperature measurement attachment (dipping thermocouple)

Recent research work, carried out with World Gold Council support by the German Precious Metals Research Institute, FEM, in Schwäbisch Gmünd, has shown that the largest percentage of defective jewellery is produced by investment casting, and that generally the defects are somehow related to temperature effects (1). The results of this research are shown in Table 1. When we consider that, at present, investment casting has become very important for jewellery production, we can easily realise that reliable process temperature monitoring and control are essential.

Nowadays, all modern equipment manufacturers take this need into more serious consideration than in the past. Presently, all commercially available good level equipment, both centrifugal and static, is equipped with temperature monitoring and control systems. But, even now, not all systems give correct measurements of real molten metal temperature.

In modern equipment, induction heating is always preferred: it is a costly option, but it allows direct material heating. Heat is generated directly in the metal to be melted and the time required for melting is minimised. As a consequence, alloying element losses are also minimised. In addition to melting time reduction, induction heating effects good melt stirring and expedites melt homogenisation. A 10 kHz frequency can be considered as an upper limit for an efficacious stirring effect. Below 10 kHz, the stirring effect is stronger, but equipment cost is higher. In both centrifugal and static melting/casting machines, graphite is the crucible material most frequently used. Graphite gives a double advantage: it provides a slightly reducing atmosphere for the molten metal, because it oxidises before the usual alloying elements, and, being electroconductive, it is heated directly by induction and speeds up melting.

As to the atmosphere, relatively few centrifugal casting machines operate in an inert atmosphere, while it has been widely adopted in static equipment. Atmosphere control is simpler in static machines, because the volume involved is smaller. In the centrifuges, the larger volume involved makes this control more difficult. Generally, in centrifuges, atmosphere control is attained by means of gas flowing out of a small tube positioned on the crucible rim. In most cases the goldsmith does not use this device, which is not very efficient. Lastly, the operation of both equipment types can be programmed, with various sophistication levels of control and automation.

Centrifugal machines

The substantial difference between centrifugal and static melting/casting machines stems from the different way used to apply the force needed to push the liquid metal in the mould in order to obtain good form filling. Centrifugal casting machines, as mentioned earlier, are the equipment type still the most widely used in goldsmiths' shops and factories.

There has been a remarkable advancement in motor technology (the oldest centrifuges were spring driven) and programming systems, but the original design remains nearly unchanged (see reference (2) for a history of the development of casting machines). In comparison with older centrifuge equipment, the most interesting innovations are: the variable geometry system, the flask with bottom applied suction and the temperature measurement attachment.

In the variable geometry system, figures 3 and 4, the angle between the flask axis and the centrifuge arm is variable and it changes from 90° to 0° as a function of rotation rate. In this way, the combination of centrifugal and tangential-inertial forces acting on the molten metal flowing out of the crucible and entering the flask, is taken into account. This device helps to improve the symmetry of metal flow and prevents the liquid metal from flowing preferentially along the side of the main sprue cavity opposite to the rotation direction, as occurs in conventional fixed geometry equipment. This phenomenon can cause incomplete filling of some items on the cast tree.

However, during mould filling in variable geometry centrifuges, turbulence of the flowing metal is higher than in fixed geometry centrifuges. To ease the outflow of the gas contained in the mould cavity and to improve mould filling, suction systems have been designed that are connected to the flask bottom, figure 5. These systems form a single unit with the rotating centrifuge part, and allow filling of very thin mould cavities, as has been demonstrated by tests carried out on 0.2-0.3 mm thick test grids (3).

Crucible geometry is very important in centrifugal casting machines. Slightly conical crucibles, with the crucible axis slightly tilted towards the outer part of the rotation circle, are used to make molten metal outflow easier. Temperature measurement is carried out with a thermocouple, figure 4, or with an optical pyrometer, figures 6 & 7. The best, but more complex, systems make use of a thermocouple dipping into the molten metal. The thermocouple is clamped on the rotating system and the electric signal is transmitted through suitable contacts, that open when rotation starts.

In some centrifugal casting machines, temperature is measured by a thermocouple contacting the outer crucible surface. In this case, the reliability of temperature readings is poor. Moreover crucible and thermocouple have different electrical potentials and electric discharges can occur; these oxidise the thermocouple junction and contribute to errors in temperature readings.

Generally, centrifugal casting machines are programmed by the operator and the interaction with the operator is very tight, e.g. he chooses the rotation rate and, consequently, the level of the centrifugal force that will push the molten metal into the mould during pouring.

At present, centrifugal casting machine development is aimed at programming improvement and process automation.

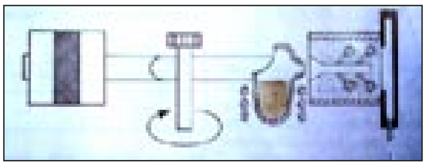


Figure 5 - Sketch of centrifugal casting equipment with suction through the flask bottom to facilitate form filling

Figure 6 - General view of centrifugal casting machine equipped with an optical pyrometer for molten metal temperature measurement

Figure 7 - Detail of the optical pyrometer in the centrifugal casting machine of figure 6

Static melting/casting machines

In my opinion, in recent years the most important progress in equipment development has been achieved in this field. Modern static melting/casting machines are "vacuum assist" and the dynamic pressure difference between crucible and flask facilitates mould filling, figure 8. In my opinion, the best melting/casting machines are equipped with separate crucible and mould chambers. One chamber can be opened, while the other one stays closed under a protective atmosphere. In this way, process time can be reduced even more.

Nearly all static melting/casting machines operate under an inert atmosphere. In some cases, a slightly reducing atmosphere is used, but, according to recent research results, this option is not recommended, because it promotes dissociation of calcium sulphate (the binder in the investment) and so increases the probability of the occurence of gas porosity. Argon or nitrogen atmospheres are commonly used: the latter one is less costly and gives very good results.

Presently, there is a trend to increase pressure on the flask when pouring has been completed and the metal is still in a liquid-to-pasty state. This method is called POV (Pressure Over Vacuum). On this subject, it is important to know how the pressure increase is triggered - by programming or by an infra-red light detector. The infra-red light detector is more failure-proof, in that the detector "sees" when pouring is over and then immediately opens the valve that puts the upper part of the mould chamber (button side) under pressure.

When the valve is triggered through the program, it is opened after a preset time has elapsed, starting from the beginning of pouring. In this case, it can happen that, for some reason, the pressure increase is triggered before pouring is over, or, if pouring is faster than expected, it can be triggered with a short delay after pouring has ended. In the first case, the probability of the occurrence of porosity from entrapped gas increases. In the second case, the pressure increase can be totally ineffective because, as solidification time is very short, solidification has already occurred.

In the latest generation static casting machines, the trend is

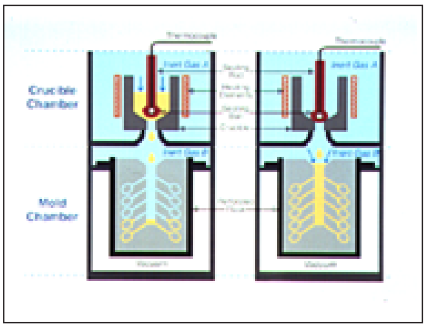


Figure 8 - Sketch of a static vacuum assist casting machine with separate crucible and mould chambers and pressure over vacuum system

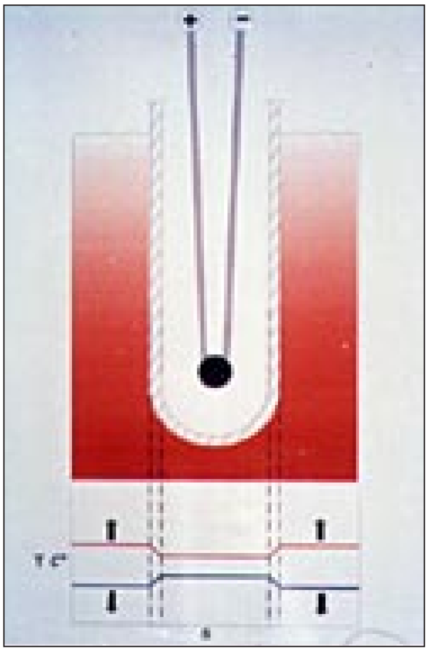


Figure 9 - Diagram of the lag in temperature measurement with a dipping thermocouple. If it is not corrected, temperature readings will be lower than true charge temperature in the heating stage (red line) and higher in the cooling stage (black line)

Figure 10 - Flask temperature measuring attachment, equipped with optical pyrometer, as installed on a NEUTEC/USA machine

Figure 11 - Examination and comparison of computer-recorded process data

towards an even more complete automation. As I have said on a previous occasion (4), in some cases a type of artificial intelligence is used: the system replaces the operator, who only physically introduces the metal charge, and it takes all technical-metallurgical decisions. So, the goldsmith can be mostly concerned with activities more congenial to him.

The more recent static casting machines can be subdivided into two groups: those with traditional computer control or those with self-programming. Personally, I call them "computer-assisted" or "computer-controlled" (4). The most important differences between these groups are that, in the case of computer-assisted machines, the operating cycle is planned by the operator, who gives the computer a set of instructions, like alloy weight, melting temperature, required electric power output, delay in pressure application, etc. Generally, data collection must be done by the operator, who should write down all data about the operating parameters recorded by the machine.

In the case of computer control, the machines are self programmed, can automatically evaluate the weight of the charged metal and correct the thermocouple temperature readings in real time: this correction is needed because thermocouples are always enclosed in a refractory sheath and temperature readings always lag behind in comparison with the true molten metal temperature (they are lower in the heating phase and higher in the cooling phase), figure 9.

There is a computer-controlled machine which uses a system that automatically measures flask temperature immediately before pouring, figure 10. This system is very interesting for process control. It should be remembered that molten metal and flask temperature are linked together: They form the "temperature system", a knowledge of which is fundamental to guarantee uniformity of quality. Data collection is carried out automatically, when these machines are connected to a PC. In any case, the collection of objective and reliable process data is very important, in order to keep the process under control and to explain the causes of any defects that can occur, figure 11. In many casting machines, pouring takes place preferably through the crucible bottom, to minimise the liquid metal path length. In my opinion, this option is safer and is to be preferred.

Molten alloy composition homogeneity is another very important aspect of investment casting: this problem, too, is frequently underestimated, and too much confidence is put in melt stirring produced by induction heating. As has already been said, the stirring effect is really effective only when current frequency is 10kHz or lower.

The use of grained alloys, either purchased or easily produced by an attachment to the casting machine, figures 12 and 13, is a good practice to improve melt homogeneity and to reduce melting time and the danger of overheating. Unhappily, this practice is still too little used.

Centrifugal or static casting?

There is only one case with a definite answer to this question: where platinum is being cast, the use of a centrifuge is strongly recommended. In the case of gold alloys, the final choice is not so definite and must be left to the individual goldsmith - but a few pertinent remarks can be made. First of all, we have seen that more technical progress has been achieved in static casting machines, where, in some cases, a near complete process automation has been accomplished. In my opinion, this possibility should be seriously considered. I have realised that very often the goldsmith isn't a technician and maybe preferably he shouldn't be. The goldsmith is prevailingly an artist and his creative attitude is best devoted to the design of new jewellery rather than to hazardous "inventions". Automated equipment can free the goldsmith or equipment operator from technical responsibilities, and should guarantee a better and more reliable product quality.

Obviously, such equipment must be reliable. Moreover, it is fundamental, and maybe it is most important for achieving good quality results, that all process steps coming before melting and casting have been correctly carried out. I will never tire of repeating that investment casting is a multi-stage process: melting and casting are only the final metallurgical

Figure 12 - Graining attachment for making alloy grains of the required caratage and homogeneity

Figure 13 - Casting equipment with the grainer in position, in place of the mould chamber

steps, but they are not necessarily the most important ones.

Coming back to our question "static or centrifugal?", centrifugal casting has two weak points: high poured liquid metal turbulence and high pressure in the flask, both produced by the centrifugal force. Both these features are unfavourable, even if high pressure facilitates complete form filling. High turbulence increases the probability of gas entrapment and favours the formation of gas porosity. The probability of the occurrence of gas porosity is also increased by the fact that, in centrifugal casting machines, perforated flasks are not used and, even if a suction system is available, suction takes place only through the flask bottom. So, outflow of the gas contained in mould cavities will be slower than in a vacuum assist casting machine.

The high casting pressure can give rise to various defects in the casting, such as non-metallic inclusions, arising from cracking or spalling of the investment during form filling. Recent research work (5) has demonstrated that surface defects caused by investment surface erosion, usually ascribed to incorrect burnout, frequently result from high centrifugal casting pressure, figure 14.

Moreover, it should be remembered that, in centrifugal casting, the maximum pressure is attained on the flask bottom (top of the wax tree), where cracks may form; the minimum pressure corresponds to the button zone. Near the button, filling of mould cavities can be incomplete: this occurrence can be due to premature partial form filling that is produced by the flow of liquid metal along the side of the main sprue wall that is opposite to the rotation direction, figure 15. In static casting, the pressure is constant on the whole tree length, and the only difference between bottom and top of the tree comes from the hydrostatic metal pressure.

The high pressure generated by the centrifugal force sets an upper limit to the weight of the metal that can be cast in a centrifugal casting machine (about 600-700 g, and no more than about 800 g), if a safe operation is desired. The flask height should be 100-120 mm and no more than 150 mm. However, in static casting machines, the weight of the cast metal can be more than 1.5 kg and flasks up to 250 mm high can be used. Larger weight and higher flask mean process economy. Process economy can be easily evaluated when the button weight to total tree weight ratio, and the "working" to "non-working" investment ratio are considered, figure 16.

In my description, the working investment corresponds to the height of the tree. The non working investment corresponds to the button zone and to the bottom of the flask. In a 130 mm high flask, 45% of the investment does not work, while in a 250 mm flask non-working investment is reduced to only 25% of the total.

Figure 14 - Defects in cast rings that can be ascribed to excessive pressure during centrifugal casting

Figure 15 - Incomplete filling of centrifugally cast items (on the right side of the tree)

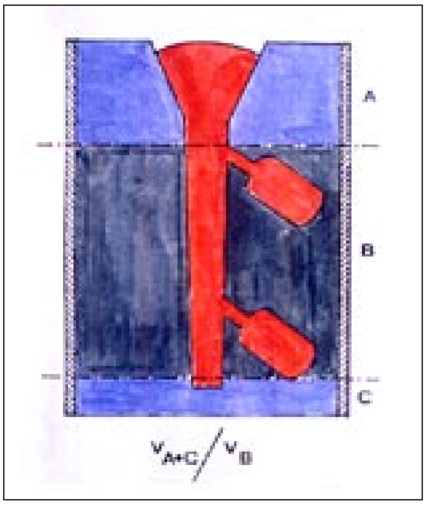


Figure 16 - “Working” (green zone) and “non-working” (blue zones) investment. The amount of “non-working” investment can be considered as constant and independent of flask height

Another remark refers to productivity. Working with a centrifugal casting machine, an operator can hardly carry out more than 8 casting cycles/hour, with 130 mm high flasks. In contrast, working with a latest generation static vacuum assist casting machine, he can cast up to 20 flasks, 250 mm high, in one hour’s work. Clearly, these are extreme cases, but they can give an idea of the potential of the two systems.

Moreover, centrifugal casting machines have moving parts and require more maintenance work.

Finally, recent research work (6) has demonstrated that, in static vacuum assist casting with perforated flasks, thanks to a simple change of tree shape, it is possible to minimise poured liquid metal turbulence and to facilitate gas outflow from the mould. By changing the gate/sprue angle from 30-45° (as commonly used) to 75-80°, with unchanged gate length, the ends of the castings are brought nearer to the flask outer wall and the path length of the gases flowing out of the mould through investment pores is shortened. On the other hand, the whole sprue-gate system is more critical in the static casting process.

Conclusions

I said before - and now I repeat - the final responsibility for the choice of equipment must be left to the goldsmith. In my presentation, I hope to have given a sufficiently clear outline of the major technical differences between the two casting systems and of the various aspects that should be considered in making a choice.

In these years of contacts with the goldsmiths’ community in many countries around the world, I have become convinced that the goldsmith can count on the patronage of very powerful saints. Otherwise, I am not able to find an explanation for the fact that very beautiful jewellery can be produced with the hand powered centrifuge or with the process of static casting under a potato’s pressure, mentioned at the beginning, as well as with the most technically up-to-date machines.

Anyway, we should remember that the saints are very busy and do not always have time to perform miracles. If we need uniform quality and high production rates, modern equipment should be taken into consideration. As a technician who is on the goldsmith’s side, I think that vacuum and pressure assist static casting can better guarantee higher and more uniform quality levels as well as productivity.

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