Planning the feeding system in investment casting processes

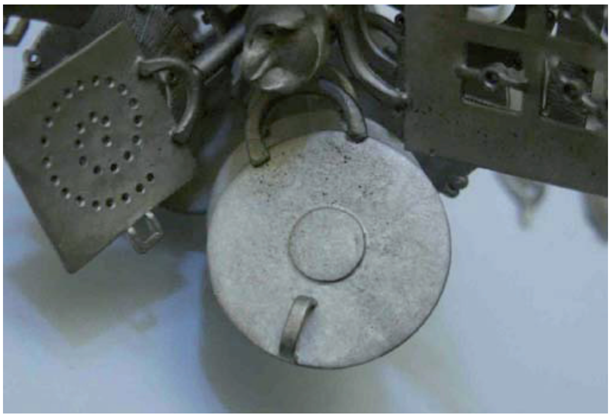
1. Introduction

1.1 The metallurgic aspect of the goldsmithery processes was disregarded especially in the past favouring so a higher attention of the artisans to the aesthetical and stylistic aspects of their creations. This involves so an empirical approach and oriented to the minimization of costs in the castings preparation, instead to a conscious approach to all those problems connected to a casting process or their possible solutions. It is necessary to remind that great part of the defects are in fact related to the rough planning of the feeding system, which is finalized to save resources instead of obtaining a defectless casting.
The preparation of the casting, instead, should take into consideration a whole series of kinetic and thermodynamic aspects together with the solidification of the cast. These two phases are fundamental for the global economy of the casting process and their correct functioning grants the final quality of the investment cast items.

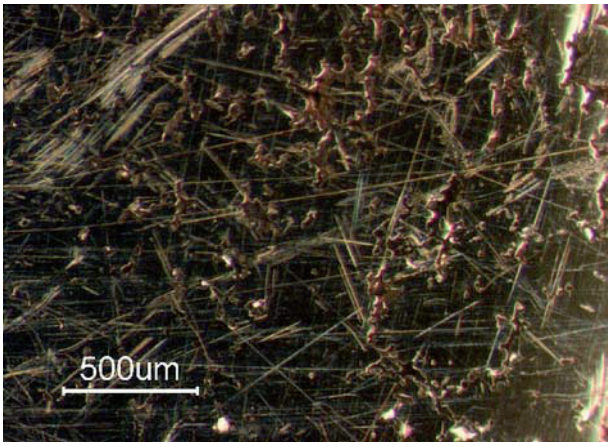
2. Typical defects of the investment cast items

2.1 The first thing to do is to analyze all the defects due to the incorrect feeding which can be found on a piece made by investment casting in order that beginning from the effects, it is possible to trace the causes and consequently the best way to face them up.

2.2 Shrinkage porosity
Shrinkage porosities are the main display of a not proper feeding system of the casting itself. In fact if the casting is well planned, this kind of defect is displayed only in restricted areas of the material, inserted in the casting with the only aim to collect all the problems of the casting itself. These areas can be feeders, sprues, tanks.

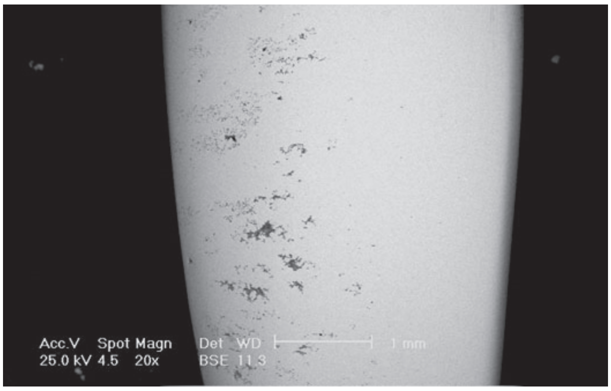


Picture 1

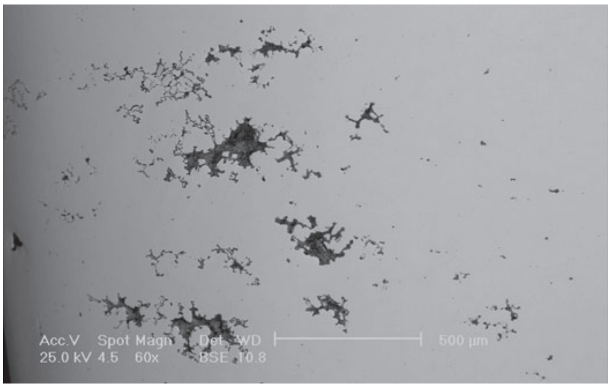


Picture 2

As you can see in these photos the shrinkage porosity can appear by any sort of mean. Particularly critical are massive pieces, pieces with big parallel surfaces and with meaningful section variations.

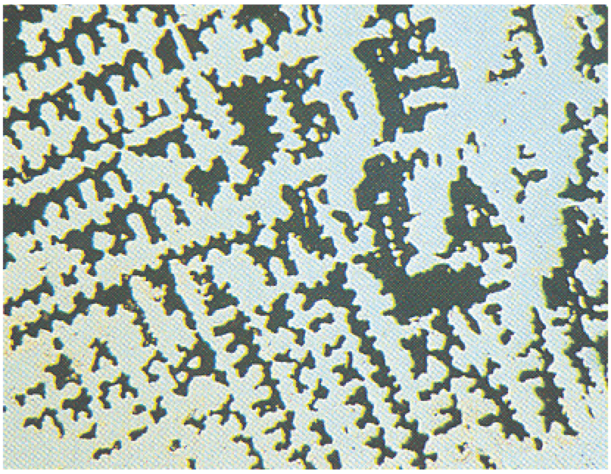


Picture 3



Picture 4

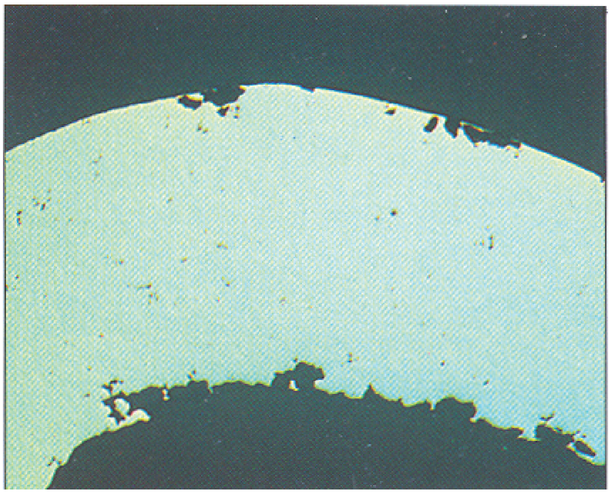
The morphology is the one of agglomerates of dendrite shaped cavities, concentrated in the areas where the problem was very much felt and which gives place to a "spongy" structure of the metal. In the worst cases this porous structure, highly dendritic, drastically reduces the mechanical resistance due to the reduction of the resistant section, drawing the piece to conditions very close to breaking.



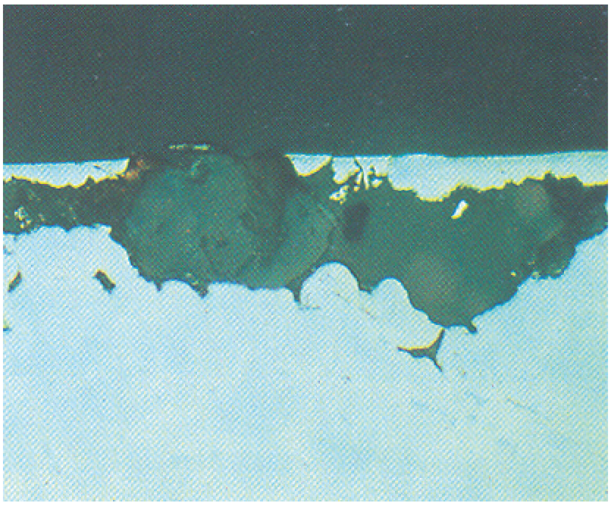
Picture 5

2.3 Inclusions

This sort of defect is mostly connected to the mould making, than to the planning itself and it is displayed with inclusions of investment on the surface or inside the metal. Pores are displayed randomly all over the surface and can be empty or still full of material which is for sure not metallic. Most probably, also the pores, which were empty during the analysis, were at the very beginning filled by inclusions which were subsequently removed by surface treatment operations such as pickling or polishing. Or even better, very often such operations, instead of resolving the problem, they wide it increasing the dimensions of the pores.



Picture 6



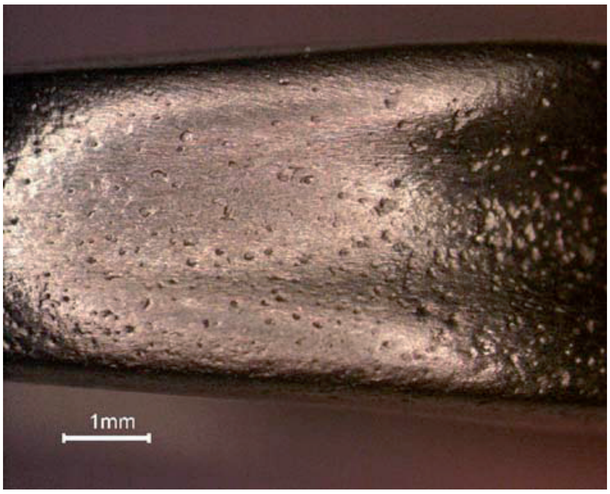
Picture 7

Extremely subjected to this kind of defect are the pieces made by centrifugal casting, where the force stressed on the mould is extremely high. For sure also the quantity of investment plays a role, but the shape we decided to give the mould plays a fundamental role.

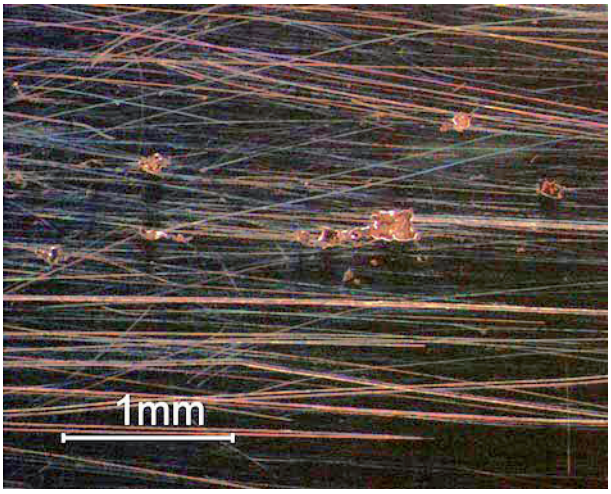
2.4 Gas porosity

Gas porosities are usually very hard to distinguish from shrinkage porosity: very often the two phenomena display with likewise the same dimensions. The only discriminant is very often the shape, rounder as far as it concerns gas porosity. This sort of defect, even if very frequent in the investment casting processes, is the consequence of a bad feeding system of the casting only in rare

or particular cases.
Gas porosities can have a double origin: they may derive from gasses formed during the decomposition of the investment, or they can derive from the gas entrapment due to the excessive turbulence. In the first case it turns out to be more critical a casting process under protected atmosphere, vice versa the second case is more frequent for casting in air, especially when hand made.



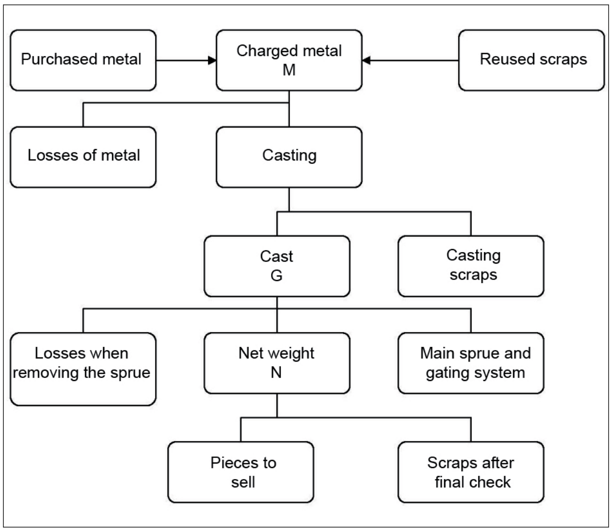
Picture 8



Picture 9

3. Theory outlines about metallurgic foundry

3.1 The theory about the foundry processes was developed mostly for the processes connected to the castings of cast iron, brasses and aluminium than the processes connected to the goldsmith world. In any case, the same theory principal are valid also for our field.
The two guide lines which rule the planning of a casting for foundry make reference to the uid dynamic processes and the processes of thermal exchange between masses at very high temperature. Particularly, the motion of a uid follows the laws described by Bernoulli and Reynolds, instead the thermal exchange is ruled by thermal conduction processes. It is not appropriate in this work to go deeper into excessive examinations on the theory, but it is more important to take into consideration the whole range of practical rules issued by these rudiments which are going to be illustrated in brief.
As a prerequisite, it is important to underline that, at first hand, a proper feeling of the casting seems to increase the production costs, since in the majority of the case, you have to increase the quantity of "scrap" material in feeders, sprues and tanks. The matter, though, should be taken into consideration with a wider perspective.



Picture 10

Defining the global performance of the process

$$R_{GLOBAL} = F/M$$

and the casting performance.

$$R_{CAST} = N/G$$

you can easily notice that a reduction of the casting performance (that is to say of the material used for the feeding system), does not automatically affect the increase of the production costs. Rather, very often, it happens the exact opposite: a tree with a low performance increases the chance for scrap less pieces due to defects among the finished products. As a consequence, more than a saving of money and material, you can also obtain a remarkable saving of time, since you do not have to do twice the rejected pieces due to non conformities. Let's see then where to start for optimize the casting planning.

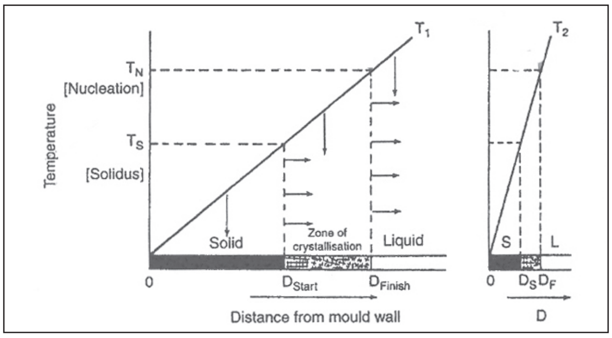
3.2 Fluid Dynamics

The uid dynamics aspect involves especially the first phase of the casting process, that is to say

the one where the metal begins to fill the mould. In this first phase the main request is for the ux of liquid metal to have a rolling motion, or at least not excessively turbulent, in order to avoid the erosion processes of the mould and the inclusion of investment material inside the metal.
The uids motion is described in the laws of Reynolds and Bernoulli. These two laws put together speed, charging, pressure, density of the molten metal and roughness of the surface onto which the uid runs.
For obtaining an ideal ux inside the feeding channel, you should either cast at very low rate (not advisable both for economic and solidification reasons) or use feeders of big dimension. The Bernoulli law rules also the choice of the metal on the way to run. In presence of branching, in fact, the metal will choose preferentially the way which involves the less energy waste. Exploiting this phenomenon allows to create, then, some ways of preferential feeding, using geometries which involves high losses of energy in the areas you want to be filled at the very latest.
In the investment casting techniques it is particularly hard to make this happen in real conditions. Reaching conditions of rolling motion is almost impossible by taking into consideration the process parameters. Luckily the filling step is not a source of great concern since defects due to an excessive turbulence are only a small percentage of the defects of the investment casting processes.

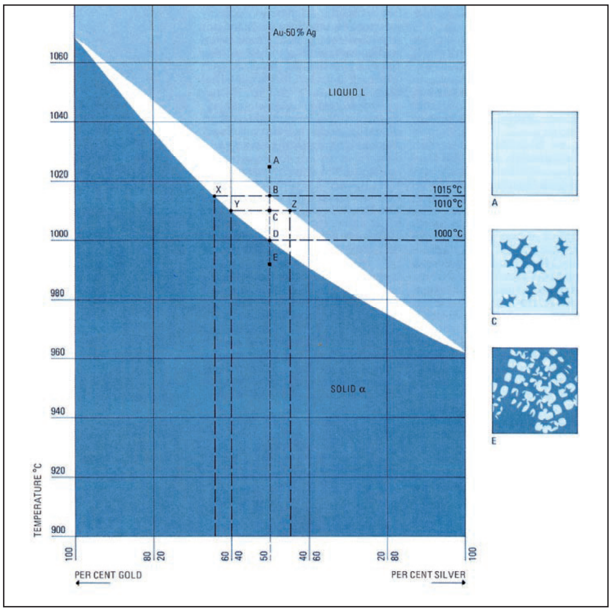
3.3 Thermal exchange

Extremely important is instead the study of the progress of solidification of the cast, since to this aspect are connected most of the defects present in pieces produced by investment casting.



Picture 11 – Influence of the temperature and composition gradiente on the dimension of the “pasty zone”

First of all it has to be said that solidification is ruled by the so-called “pasty zone” (see picture 11). Since we are not dealing with pure metals, solidification does not take place at a specific temperature, but at a range of temperatures between solidus and liquidus.
The solidification front so, shapes in an area which is neither solid nor liquid, where the first solid germs start to nucleate and grow. During the solidification extremely critical situations for the material can happen: since, as before said, you are in presence of alloys of materials and not of pure metals, during solidification there are segregation phenomena of some elements in the liquid which remain around the grains while shaping (picture 11). Step by step the process goes on, the pasty zone can have a composition which becomes more critical once the solidification proceeds. When the last liquid solidifies, this is going to be of a totally different composition to the nominal one and can give place to defects due to macro segregation phenomena. The aim is therefore to make the last solidification happen in those areas where the presence of porosities and segregations cannot cause problems to the piece.



Picture 12

Another aspect to consider is the one of the volumetric shrinkage due to solidification. Most part of the materials in fact reduces the volume once the temperature decreases, and particularly when the passage from the liquid to solid takes place. If the casting is properly fed, the shrinkage of each single portion of material which solidifies is constantly compensated by the feeding of new uid material.
The solidification front so, following the same path of the pasty zone, has to be “directed” to areas where it cannot bother once also the last liquid solidifies. In this moment in fact the shrinkage will be inevitable. It is important that this happens in areas where the concentration of material does not cause problems (neither aesthetical nor mechanical) to the piece.
The thermal exchange is fundamental for these kind of processes. In fact ignoring the contribute given by the concentration gradiente (assumption that can be made only at a primary analysis), you

can tell the solidification area and the pasty zone follow the behaviour of the thermal gradiente, i.e. the solidification will take place in areas with a higher super cooling, moving then towards warmer areas.
In case of pieces of simple geometry and castings for single pieces, the performance of the temperature gradiente is almost predictable. You cannot tell the same though with regards to a normal tree for investment casting. There are plenty factors which in uence the performance of the thermal gradiente.

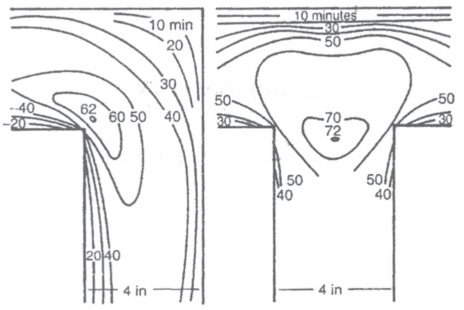


Figure 3.5 Effects of external and re-entrant corners on local rates of freezing: end of freeze waves after successive intervals (from Brandt *et al*[30]) (courtesy

Picture 13 – Effect of the edges on the cooling gradiente and cooling waves at further ranges

A first example can be the presence of angles or pieces in the vicinity which, as it can be noticed in picture 13, modify the temperatures inside the piece.
Another example can be given by a very high concentration of masses which modifies once again the performance expected by the thermal gradiente. We will discuss this very last aspect in deeper details in the further sections.

4. Principles for the correct planning of a casting

4.1 The model

The point where to start from is the investment casting process. The model can be handmade or made by using the most modern techniques of the cad cam (this last one is the fastest and most precise one). Usually it is made of metal or wax; the first ready to be rubberized; the second one to be used as a mould to prepare the metal model.
In both cases for producing the metallic model, it is advisable to use brasses made purposely for casting (of high mechanical features) which grant very few defects by casting and high hardness, a key feature for a good finishing. In order to improve even more the surface quality of the model you can make it undergo galvanic processes such as Rhodium plating, Copper plating or Nickel plating.
A high surface quality of the model is basic to avoid the surface defects to be reproduced first on the wax models and then on the casting causing defects, which during the quality test, may be wrongly evaluated.
In second instance beginning with a mould with an adequate surface finishing helps to avoid to give the cast a very poor surface quality.

This device draws to have to benefits:

- Having a mould with very low roughness means to have potentially a piece with very good surface quality;
- A mould with a very good surface quality displays a low coefficient of friction allowing the uid to run better and avoiding excessive turbulences which cause, as seen before, problems of mould erosion and inclusions of gas and investment.

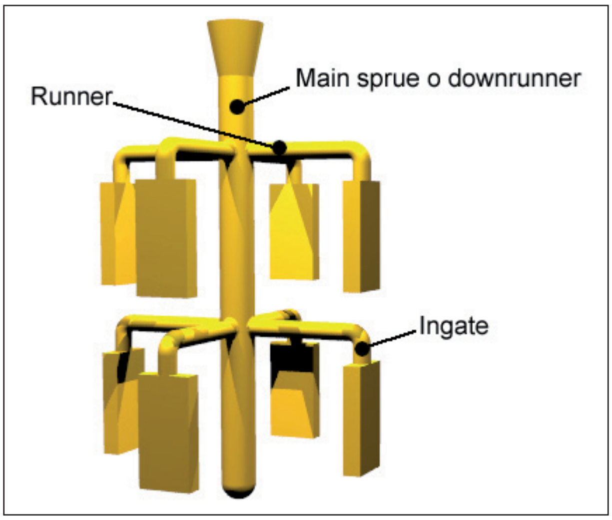
It must not be forgotten that the reproduction of extremely fine particulars is impossible when a proper surface finishing is lacking.

In general, it is recommendable to plan and realize the model using the cad cam technology. In this way the dimensions and geometries of the model are defined and controlled already beginning from planning. You can therefore avoid problems connected especially to the non homogeneity of the various sections dimensions, reproducing therefore with accuracy the model provided by the designer. It has to be underlined in fact the importance of having homogeneous thickness to avoid shrinkage concentrations defects in bad made areas.

4.2 Feeding system - Introduction

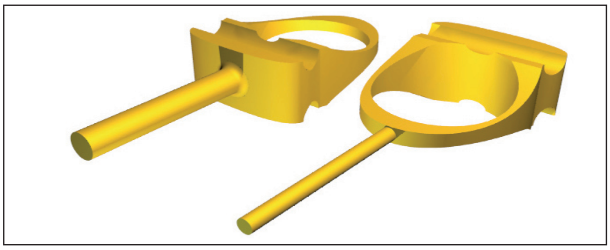
This work is a general overview on the rules to follow for all the setting phases of the waxes on the trees. Then, basic rules are discusses about the feeders dimensioning, to chose the number and the position of the same on the pieces.
It has to be reminded that most part of the defects on investment cast pieces is connected to a summary planning of the feeder, which is made purposely to save time in cutting the same or to save material, instead of obtaining a piece defectless after casting.
For such reasons, we would like to convince the operators to give less importance to the points we are going to discuss further.

4.2.1 The feeder



Picture 14

In order to size main sprue and runners, you have to establish a suitable number to guarantee the feeling of metal inside all the pieces; in small words, while usually the main sprue is only one, there can be at the same time several runners. The first sizing can be obtained by calculating the range of masses necessary to obtain the filling of the piece according to the time and the speed of the casting process.
In second place, also the ingate section has to be suitable and respect the more the possible a ratio of 1:1. This is to say, the dimensions of the section of the ingate should be likewise the dimensions of the section of the piece which ingate is placed.
It is usually advisable for all the elements of the feeding system to have a rounded section both for uid dynamic reasons and thermodynamic ones.
As for the uid dynamic aspect, the friction is related to the surfaced and the speed; so, the rounded section for the same load offers a surface and a friction lower than any other section. The less friction the uid has, the more inferior is going to be the turbulence on its motion and consequently the chance to have gas porosity or inclusions is going to be reduced. With regards to the thermodynamic aspect, instead, the dimensions of the feeding must be enough to ensure the molten metal not to "jell" before the filling has taken place. This can be obtained with two of the dimensions sufficient big both for the main sprue and the ingate and runner.
Never the less, the position is always a very important aspect for planning an adequate feeding system.

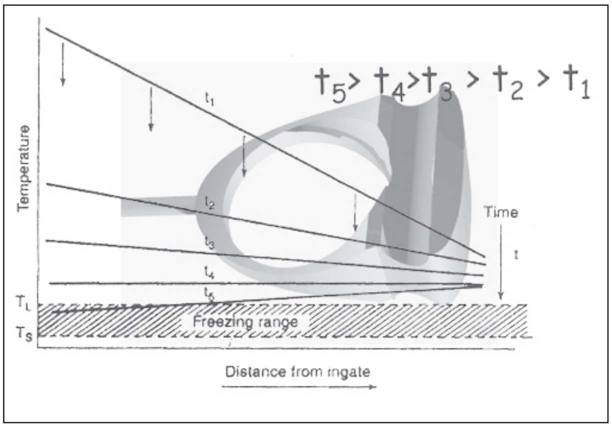


Picture 15

As general outline, you can place the ingate on the most critical areas for filling the items, i.e.:

- In the heaviest part of the piece (where the biggest mass of metal is concentrated), (see picture 15);
- Next to section changes or marked angles;
- In a position which allows setting the piece and being sure that area is going to be the last one to fill and solidify.

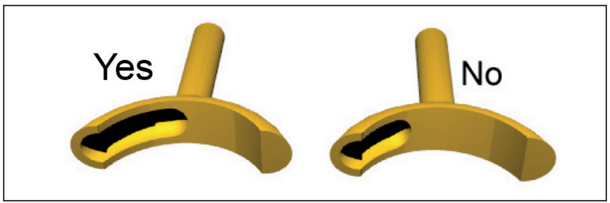
This last point is very complicated to solue. In fact, for simple geometries, the performance of the solidification front is easily predictable, the same cannot be said at the moment when you have to deal with pieces which make of design their peculiarity.
As already said the performance of the solidification front follows the temperature gradiente.
When the casting though displays particular shapes, the temperature gradiente, which is not constant in time, may take performances totally unpredictable. Going back, for example, to the case of the piece with big mass differences (picture 14), you can imagine a performance of the gradiente as illustrated in the following picture:



Picture 16 – Variation of the temperature gradiente in time

The right hand side of the drawing above reported (picture 16) corresponds to the highest massive area of the ring. As soon as the material is cast, the maximum temperature is going to be close to the ingate since a thermal exchange with the external part of the ask is promoted. As time goes by, due to the high thermal inertia of the massive part, you will have an inversion of the thermal gradiente.
As a result, the part which is going to reach the temperature for starting the solidification will be the closest one to the ingate and not, as it happens in most cases, the most external part of the piece. In such case, the feeding is going to be obstructed by solid material even before the piece to be completely solidified, drawing, at best to very evident shrinkage porosities until getting, at worst, to pieces of a shape which does not correspond exactly to the mould one. This can be explained by saying that the material

during solidification tends to shrink. For compensating the shrinkage some other metal is going to be constantly attracted from the ingate. But if this one is already solid, it won't be able to take some new material and as a consequence the empty space due to the concentration is going to remain the same. According to the seriousness of the phenomenon you will have porosities or even shrinkage cones on the surface of the pieces.



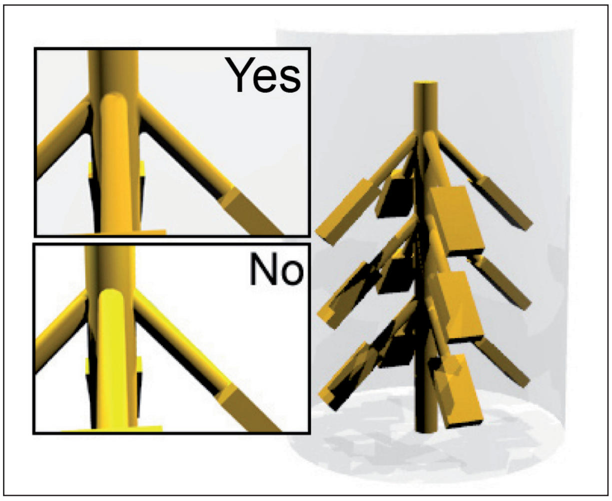
Picture 17

As far as it concerns the position, we are going to proceed by giving you some examples. Pretty much always rings display significant reductions in section (to reduce the weight); by looking at picture 17 you can clearly see it is a piece which section undergoes a neck-in. Is it there you have to place the ingate? The ideal is to place the ingate both before and after the neck-in itself. In case the ingate is placed before the neck-in, for sure the tight part will display shrinkage porosity. In this case, you should opt for placing the ingate on axis, with the aim to distribute the metal a little some on one side and a little some on the other. A very much used alternative solution is to use multiple ingates (see picture 18). Each ingate can be placed in each one of the critical areas, or more than one is used to improve the filling of the pieces made of very much complicated geometry.

Picture 18 – "V shaped" feeder

4.2.2 Waxes soldering

The welding point is of very much importance. In fact, when the metal goes into the ask in presence of an acute angle (consequently a sharp edge, because there is no radiation), it may break the investment and the fragments may be introduced inside the cavities of those which will then be our items. These drifts can then cause defects (for example, holes) which, at blind eye, can be confused with porosities, pushing the operator to correct the casting operational conditions (for example, the asks temperature and the metal), when it was probably enough to pay some more attention while setting the waxes, trying to make the contact points (see picture 19), that is to say those which form a sharp angle are radiated instead.

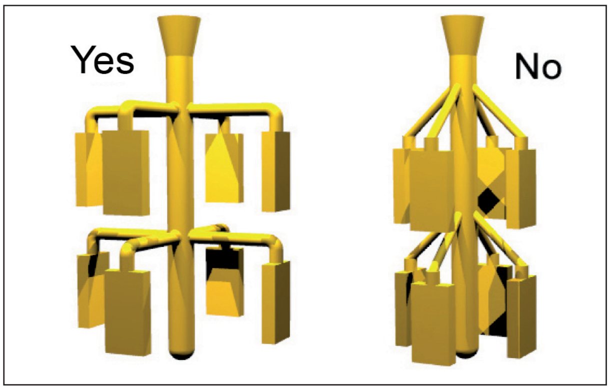


Picture 19

We think it proper to underline that the phenomena is most probable in the casting systems where the incoming speed of the metal is high and, as a consequence, also the kinetic energy is higher.
Particularly, for those who use centrifugal systems, this is the most delicate point, since the chance for such mistake to cause defects. On the other hand, it has to be outlined the resistance of this point depends also on the mechanical features of the investment. It would be appropriate so to pay very close attention in choosing the quality of the investment and likewise by preparing it. It is therefore necessary to follow the instructions given by the producer with regards to the mixing and calcinations phases.

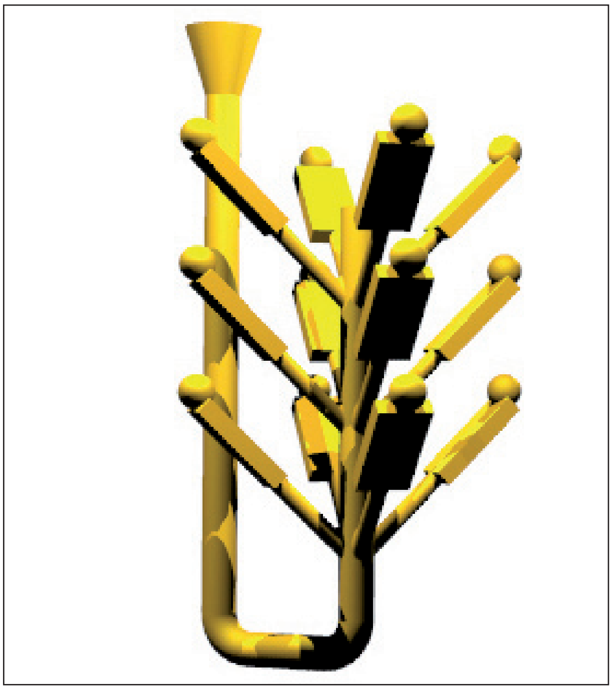
4.2.3 Setting angle - Runners

As mentioned bifore, the setting angle of the runners highly in uences the pieces filling. The ideal position, as it can be seen from the left hand side of picture 20, is the one which avoids that the first ux of metal, or a part of it, fills the pieces without following the principle of the communicating vessels, that is to say also the higher pieces begin to fill before the level of molten metal in the main sprue reached their height. On the contrary there is the risk for the higher pieces to be filled at different instances and not with a constant ux of molten metal. In the piece drawn on the right hand side of picture 20, the metal should get inside and partially fill the piece, while the second wave of metal, which is going to completely fill the piece, is going to aggregate to the part already solidified. In these conditions, it is almost certain that at this stage the defects will display.



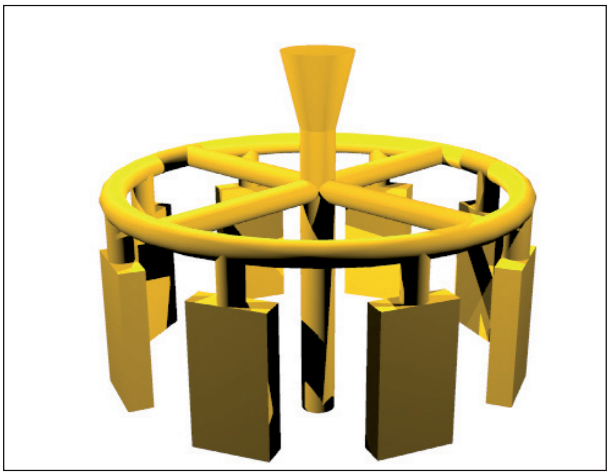
Picture 20

By taking into consideration the fact that, the chance for the metal to get into the runner is inversely proportional to the angle between this last one and the main sprue, to ensure this not to happen, the ideal thing to do will be to do angles of 90°C. In this way, in fact, you maximize the losses of uid charge which, as a consequence will hardly deviate the main runner during the first casting phase.
A further improvement may be obtained feeling the piece from the bottom, but this is not a common practice of golsmithery.



Picture 21

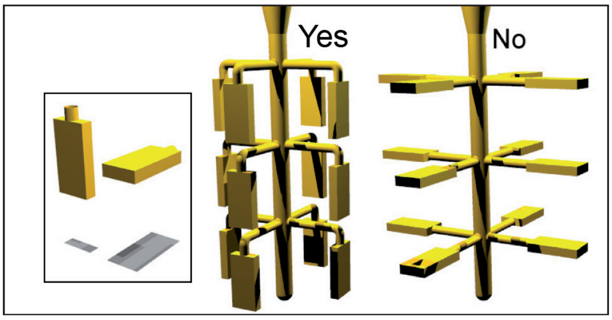
Feeling from the bottom takes plenty advantages such as the scarce erosion of the mould and a better feeling. In such conditions, the turbulence of the molten metal is almost null. On the contrary with this kind of feeding, the analysis of the temperature gradiente performance in time is a way more complicated, together with giving problems of wax scrorification
In spite of this, such solution may give extraordinary results.
A more common solution though it the one displayed by the next picture:



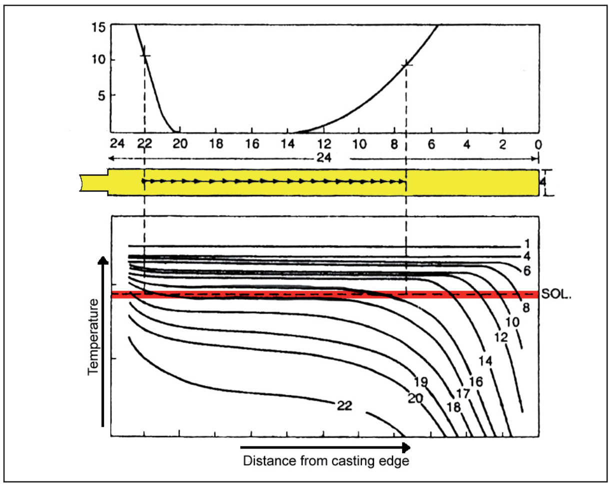
Picture 22

4.2.4 Setting angle - Pieces

The setting of the pieces can follow at first instance a very simple rule. The projection of the piece on the horizontal plane has to be the smaller the possible. This rule is a way to summarize a bigger concept. We take as example the medals in picture 23. In case it is set on a horizontal position you have the situation illustrated in picture 24.



Picture 23

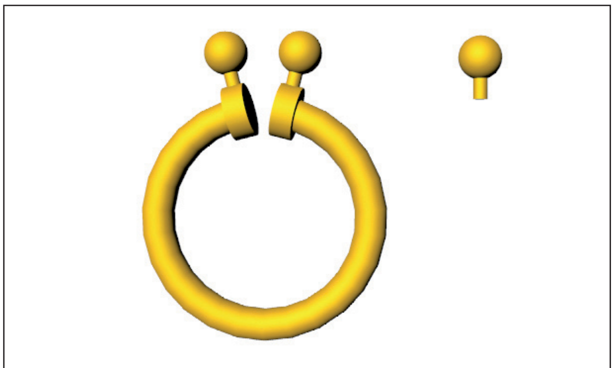


Picture 24 – Temperature gradiente performance of a medal placed horizontally in function of time and distance from the feeder.

The waves on the bottom part of the picture display the performance during an amount of time of the temperature gradiente. It can be noticed also that between 16 and 17 minutes a big part of the medal reaches the solidification temperature. All this material can contemporaneously "jelly" compromising the injection of new liquid to compensate the variation of volume typical of a passage liquid- solid. Consequently on the upper part you will have evident porosity if not a real shrinkage cone. If instead the medal is set in vertical position the portion of metal solidifies at the same time, it is restricted. The injection of new liquid metal it is not rested then, and further shrinkages may be directed to areas outside the piece. A corollary, then, to the previous rule may be to place the parallel and wider surfaces the most vertically the possible as illustrated in picture 23.

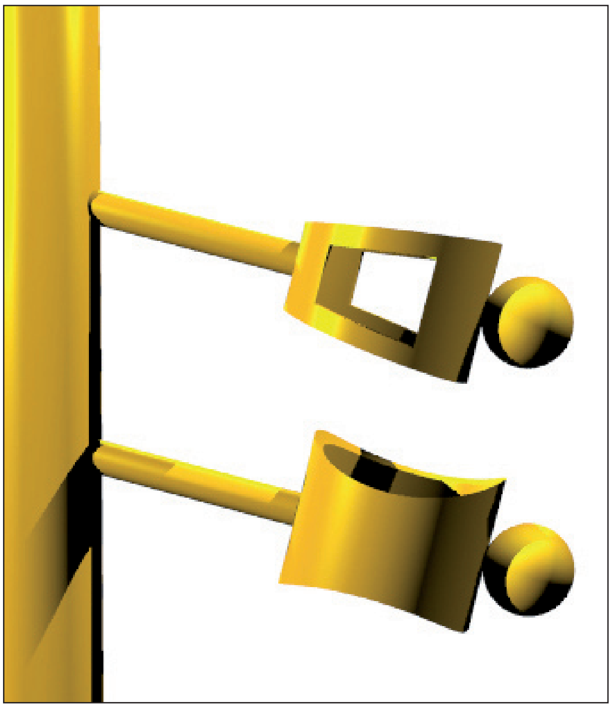
4.2.5 Tanks or thermal flywheels

In case it is not possible and you do not think it is appropriate to provide the piece a feeding, which, by itself, prevents the shaping of shrinkage defects, you can use some tanks to place in different points of the pieces; these tanks or ywheels do nothing more than contain a metal reserve for all those areas that cannot be reached by the feeder, or that display critical geometries anyways.



Picture 25

These volumes, more than being tanks for the material used to take metal also during the solidification phase, they can be used also to overview the performance of the temperatures. They allow in fact to maintain warmer, for a longer amount of time, areas where you risk to have a premature solidification.



Picture 26

These small tanks, as it can be seen in picture 25 and 26, should have a very short ingate and of rounded shape (the sphere in fact is the solid which guarantees the less loss of energy compared to the quantity of energy contained in any other solid). The tank should be placed in those massive areas that are not accessible with an ingate. Differently, if we were in the situation when the piece of constant thickness displays a hole or an opening due to the shape or the model style, the whole part of the piece under this hole should be penalized during the solidification. In fact as it can be seen in picture 26, the areas where the hole is placed are going to solidify earlier due to the minor quantity of molten metal (less mass), with the consequence that the area below may display shrinkage porosity. Also in this case, the use of a tank next to the critical area, may help to resolve the problem.

4.2.6 Tank and ingate together

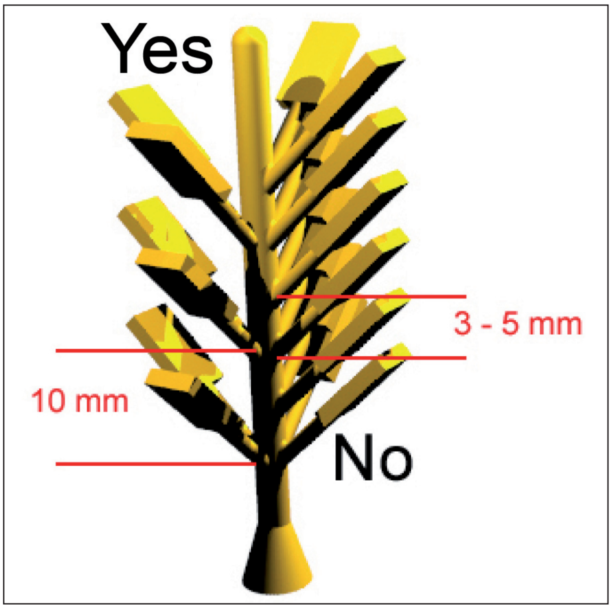
Another way to use the tank may be employing it to avoid setting an ingate of too much big diameter. Another task of the ingate is in fact to take the material to the casting for filling them. Not less important is though the thermo dynamic activity made, which takes it to remain liquid for the whole amount of time necessary for the piece to solidify.

In fact by the ingate (as already mentioned) the metal is sucked when still molten at the time when the last part of the piece solidifies and contracts. In order for this to happen it is necessary for the ingate to remain liquid until the piece to solidify. In many cases, the ingate, to meet these needs, should have a very big diameter, and not always this solution is appreciated in the production realities since it is invasive if compared to the surface of the piece. In fact, when the piece is removed, the area where the ingate was stuck is damaged. The bigger this area is, the more difficult turns out to take the piece back to the wanted shape. Consequently the goldsmith work becomes a way longer.
You can so obtain for setting the tank in order for this last one to maintain a temperature needed to preserve the ingate by solidification. In picture 27 is illustrated this kind of practice.

Picture 27

4.2.7 Distance among the pieces

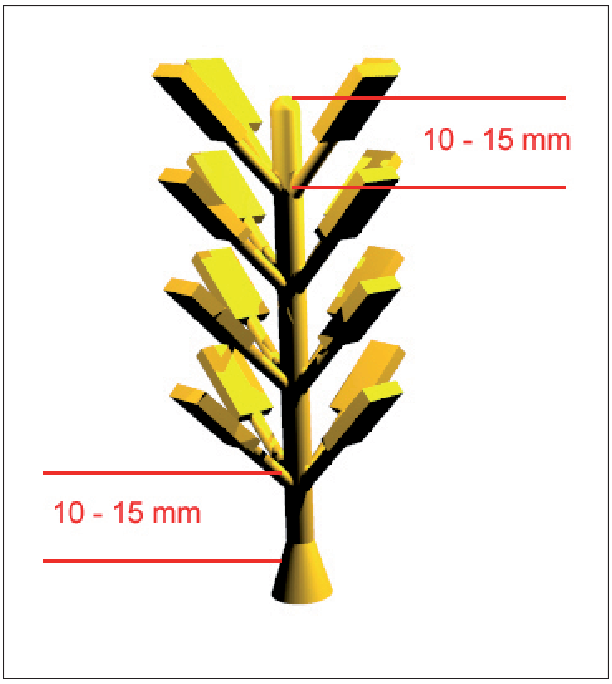
While assembling a tree it is advisable to set the pieces not too much close one to the other, since in many cases it happens that the piece display defects only on one side. This fact depends on the thermal in uence exercised on the close piece, which retards its solidification.
In small words, the pieces in uence each other as for the solidification time, which is not only connected to the shape of the piece, but depends also on the fact the quantity of investment which divides them is inferior and undergoes higher temperatures, since the mass contained in the ask in higher. This basically creates a big confusion as far as it concerns the solidification time and the solidification hierarchies of the piece itself. In fact, they do not depend not only from the shape of the piece (i.e. by all the calculation made, the considerations made for the number of feeders, the position of the feeders etc.), but it interposes a further variable displayed by the in uence of the pieces close to the each others have on the solidification. So, the whole planning work made above ceases and you are in the situation to have pieces with defects most of the times due to contraction, so to shrinkage, even if on paper the planning of the feeding system is correct.
For sure it may be appropriate to place less items possible in the ask for them to have enough place among each others. By the way, this reduces the production capacity and, like all the processes that aim to obtain the best quality, the cost tends to increase. To reduce the more the possible the thermal in uence you should set the pieces enough distant one to the other. It is to say a distance that has to be so to avoid a thermal altered and not homogenous exchange among the pieces. There are not general rules since the distance has to be chosen according to the dimensions and the geometry of the piece.
For example in picture 28 a distance of 10 mm may be enough.



Picture 28

4.2.8 Distance from the extremetie.

Another important thing is the distance between the extremity of the ingate and the sprue (final part).



Picture 29

This might be estimated between 10 and 15 mm (picture 29).
It should be of the same dimensions also the distance between the last piece and the extremity of the tree. This is aimed to limit the effect of the turbulences generated by the ux of liquid metal that, once arrived to the end of the main sprue, begins to fill it.
The result obtained is the reduction of inclusions and turbulences as far as it concerns the extremity of the tree, while with regards to the sprue, the thermal in uence and the shrinkage defects connected to it decrease.

5. Conclusions

5.1 We have outlined a brief overview of examples about how to plan and make trees and feeding systems systems.
We do not have as final aim to state absolute rules on how you have to proceed, but we are trying to direct the operators of the sector to take into consideration during their daily job the points we have faced together. For sure the calculation to do for the position, the number and section of the feeders can be more complex and they do not justify the planning cost: the pieces produced in the goldsmithery field do not have a high edition, so you need to take into consideration the basic advices to proceed in a good way and optimize the costs of everyone's own production.
If we check statistically how the most part of the companies act, you can note for sure that seldomly all these basic examples of tree planning, its architecture and the sizing of the feeders are followed. Very often such companies assert that their pieces do not have defects and do not have problems of such kind.
For sure, for the type of piece in question they succeed in finding a compromise because, even if the architecture of the tree setting is not optimal and the feeders not correctly placed or too small, they obtained good results.
This happens when companies can find their equilibrium personalizing a whole range or variables (piece shape, exercise conditions, such as temperature of the metal and ask, dimension of the ask, diameter of the ask, used investment, machine utilized) to reach acceptable results.
In each case buying raw materials, master alloys and machinery of high quality and following the theory rules which were discussed so far, you will be in the position to have a more stable and solid working cycle and not only on a specific piece, but also in case you want to diversify the production.
The aim of this study is this one. For sure a very expert person, even if not having correct feeders and to respecting any of the principle mentioned, could obtain discreet results, but not in a stable and constant way as if respecting such principles.
Our aim is to spread the most the possible a fund of knowledge to make qualitatively grow the goldsmithery sector, and according to this, also the economic benefits which may derive.