Physical, Metallurgical and Chemical Processes in Jewelry Casting

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Abstract

In part physical processes at casting can be modeled if using considerably simplified models. Besides simplification the missing of liable values for parameters is the most restricting factor. For a first attempt estimations were made using values given for pure gold and some sole values for binary gold alloys.

For all that insights in some processes of investment casting could be given. Melt flow with static casting could be modeled to some extent.

Transferring the model to centrifugal casting produced a surprise. The usual theory says that centrifugal force respectively centrifugal acceleration is the determining parameter for melt flow and formfilling. A model based on this assumption delivers very high values for the speed of rotation. Experimental work, however, shows that formfilling occurs within the acceleration phase and with a very low speed of rotation (about a tenth of the computed value). A new modified model has to be evaluated, and experimentally tested.

The thermal processes could not be modeled yet. Experimental results give some information on processes. Thin walled parts commence solidification within less than 1 second. The low thermal conductivity of investment prevents usually mutual interference of different parts during solidification. The danger of 'hot spots' is relatively low.

Other problems like metallurgical processes, and chemical reactions have only been touched. They were already subject of numerous publications.

Introduction

The success of a casting procedure depends on many factors. Each single factor can be described in principle by physical, metallurgical and/or chemical principals and laws. A great variety of mathematical equations might outline the principles. It should be possible to establish models.

Unfortunately, three main difficulties exist:
a) For an exact description a great number of parameters has to be known. However, only very limited information on such values are available for jewelry alloys.
b) The various principles are connected, and form an almost impenetrable network.
c) It is almost impossible to keep the conditions completely constant within series of castings (examples will be given later).

Now, the question will arise why we should go into this subject at all. The reason for is fairly simple. Even if we can not 'compute' the quality of a casting, we can improve the quality and optimize the casting procedure if we understand the principles. With some effort (and luck) we get a rough approximation of the real process.

In the following some selected aspects of melt flow, thermal behavior of the metal at solidification etc. are considered. Chemical aspects which involve reaction of investment with the melt are only touched, they were already considered frequently in previous publications and in presentations at the Santa Fe Symposium.

Some subjects are treated more detailed, others more sketchy. A complete treatment of the problem was not possible.

Experimental results are included were ever possible and essential.

Some remarks on results of computations are necessary:
All results are only approximations. Assumptions and simplifications had to be made to allow modeling. Most of the material

constants used for computing are only known for fine gold. Using them for yellow gold alloys is a very rough approximation.

Survey

In principal a casting process can be subdivided in several parts as is demonstrated in table1.

Table 1:
Classification of steps in investment casting

| Melting | Heat generation, -transfer |
| | Chemical reactions (crucible, atmosphere) |

| Casting | Pressure Melt flow |
| | Investment: gas permability, strength |

Solidification	Heat flow
	Structural problems: Shrinkage, grain size e.g.
	Investment: Thermal stability, chemical reactions

Melting

Melting of metal for investment casting can be performed with several methods:

Separately melting in a gas or resistance heated furnace (frequently used in silver casting),

Melting incorporated in casting equipment: Torch melting, resistance heating, and induction melting.

Recently the most frequently used melting procedure is induction melting. Therefor some remarks should be made on this method.

A medium to high frequency current generates a magnetic field in a water-cooled (primary) coil

The crucible with the metal to be cast is brought in the core of the coil. It acts as a short-circuited secondary coil. The short circuit eddy current introduces energy into the metal and causes eventually melting.

The advantages of this method are (in ideal case):
a) The heat is generated within the material, no heat transfer problems occur (in principle)
b) The crucible (if it has a high electrical resistance) remains comparatively cool. The relatively low temperature reduces the reaction between melt and crucible in critical cases (such as melting platinum). Resistance heating, for example, needs considerable superheating of the crucible wall if a short melting time is required.
c) A great amount of energy can be transferred in a short time (depending on power output of the generator). That means short working cycle, higher energy efficiency and less reaction of material with atmosphere.
d) Melting can be performed in any atmosphere (contrary to torch melting, for example)
e) The high (or medium) frequent eddy induces a stirring effect, which is particularly useful in closed chamber casting equipment.

However some special facts have to be considered. The skin effect is considered in a little more detail.

Skin effect

The penetration depth of the high frequency eddy current into the material depends on electrical properties of the metal and current frequency.

It is directly proportional to the square root of the resistivity and inverse proportional to the square root of the frequency

Fig. 1 demonstrates an estimation for penetration depth as a function of frequency. The definition of penetration depth is:

> Only one third of the energy delivered from the coil goes deeper than the given value, two thirds are absorbed within the surface layer.

The diagram shows that with high frequency current almost all the energy is absorbed in a graphite crucible wall of 5 mm thickness. Only with medium frequency more or less energy is brought in to the metal directly.

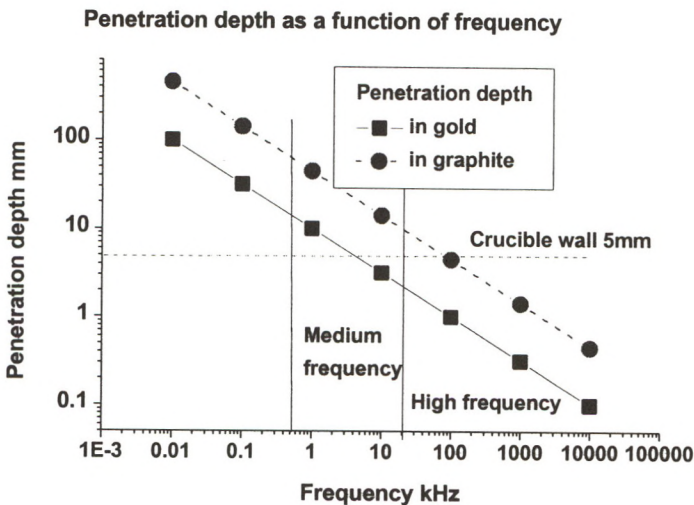**Penetration depth as a function of frequency**

Fig. 1
Penetration depth of eddy current as a function of frequency at investment casting

There is an other relation telling that an optimum of heat transfer from coil to material is achieved if $9/d \sim \frac{1}{4}....\frac{1}{3}$, d is the diameter of the sample, 9 the penetration depth.

That means:
a) For small quantities a high frequency equipment is more efficient (crucible problem not considered)
b) For greater quantities a medium frequency equipment is more suitable

In reality, an optimum frequency can not be determined. The reason for this is: as long as the material is solid a homogeneous sample diameter d does not exist. Different size of grains, scraps and other remelted material would theoretically require changing frequencies. Also the total quantity of material will differ in many cases and different alloys with different resistivity will be used in normal casting shops.

It has also to be mentioned that the total electrical resistance is the critical factor for establishing a short circuit shortcut eddy current generating the heat. For example, a heap of oxidized scraps has a high overall resistance. It will be difficult to melt this material in a short time. At least some large pieces of solid material should be present to enable sufficient coupling.

Regarding these problems high energy absorption in a graphite crucible wall changes from a disadvantage to an advantage. The crucible acts as an energy transmitter in the case of varying quality and quantity of material to be molten.

Mechanical Problems: Pressure

The mechanics of liquid metal during the casting process is one of the most important factors influencing casting quality.

The best method for describing the process is using pressures (instead of forces as in the case with solid material).

The so-called 'static casting process' (pressure assisted, vacuum assisted and combined methods) shall be used as base for describing the process. In a first approach centrifugal casting could be regarded as a static casting process with some special conditions. It will be examined more tentatively.

An important statement has to be made on this place:
The 'static casting' process is as well a dynamic process as centrifugal casting. The only difference is that in the first case the flask remains unmoved whereas in the second case the flask is moving around. Melt *flows* in both cases.

Static Casting

Fig. 2 gives a schematic figure of equipment with some characteristic parameters used for developing a model. The treatment of the problem needs a significant simplification: It is assumed that only rods of different diameters are cast without any gating.

Approaching the problem can achieved in the best way to split up the active pressures in different classes:
a) pressure forcing the melt into the pattern: *filling-pressure* (*'forward'*) and
b) pressure counteracting formfilling: *back-pressure*
Both types of pressure can be divided further. In table 2 a summary is given.

The final balance can be made by:

Residual pressure (p_{res}) = sum of filling-pressure – sum of back-pressure
In the case of a complete formfilling the residual pressure must be equal or greater than zero.

Only the static pressure p_l is really a static value. All other parameters are changing with time and flow rate, they are dynamic.
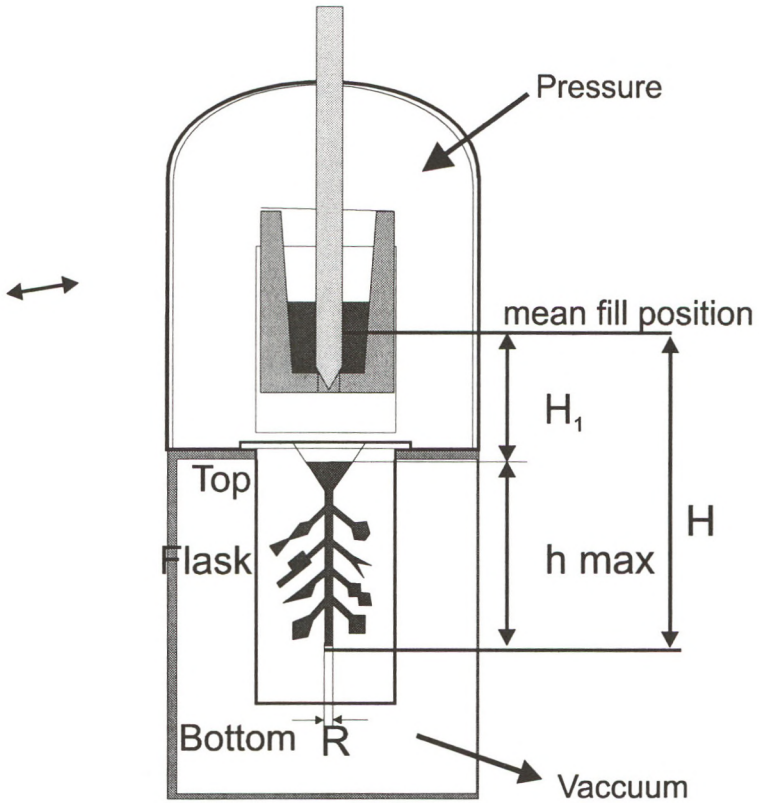
Fig. 2
Schematic diagram of a static investment casting equipment

Table 2 Pressure balance at static casting

Filling-pressure		Back-pressure	
Type	Parameter	Type	Parameter
Hydrostatic pressure P_1	Filling height of flask (h), density , h will be also named column height	Flow (resistance) p_v	Viscosity of the melt, laminar flow assumed
		Turbulence (flow) p_t	Non laminar flow at higher flow rate
Total hydrostatic pressure p_2	Distance between crucible and flask + Filling height (H), density	Surface (tension) p_s	Surface tension, increase of surface
Additional pressure p_3	Pressure from outside by applying pressure or/ and vacuum at casting	Capillarity p_c	Capillary force, interface tension
Total (filling) pressure p_3	$p_3 = p_2 + p_a$	Gas pressure p_g	Compression of residual gas, gas permeability of investment
		Balancing pressure p_s	Disturbed flow on edges, inhomogeneous structure e.g.
		Pressure caused by turbulence p_T	Structure, high flow rate

Some explanations are necessary.

The static pressure p_1 can easily be determined from the high of the melt column in the flask. It ranges from zero on the top to a maximum value on the bottom. A complete formfilling can not be achieved only by this pressure. The hydrostatic pressure is increased by the kinetic energy of the melt flowing from the crucible. However, the melt must flow into the central sprue undisturbed. If the melt meets the wall of

the funnel at the top more or less energy is absorbed by the wall. For this reason the total hydrostatic pressure may vary in an unpredictable way.

An additional pressure p_a may be added by increasing the pressure in the chamber immediately after filling the flask (pressure assisted casting) or by applying vacuum on the bottom or through perforated walls of the flask (vacuum assisted casting) or by combined methods. In all three cases the pressure difference is acting. The pressure difference can not be build up instantaneously. More or less time is necessary depending on process and equipment. Taking into consideration that the solidification of fine structures occurs within seconds (or less); the active pressure difference for formfilling is usually less than the finally measured value.

An important back-pressure is the one caused by the **melt flow** (flow pressure). For obtaining a good formfilling the melt must fill the item in the short time, before onset of solidification. Therefor a sufficient flow rate has to be maintained, causing a back-pressure. The viscosity of the liquid is an important factor. Viscosity is a material constant depending also on temperature. Values for jewelry alloys are not available. Only estimations can be made using values for pure gold and some binary alloys.

Melt flow can occur in a laminar flow. The corresponding pressure p_v can be roughly estimated as function of flow rate and geometric relations for a simplified model.

Beyond a certain critical flow rate and also due to inhomogeneous structure in the flow channel (that is the item which should be cast) **turbulence** occurs which increases the back-pressure considerable ($p_t > p_r$). Even an approximate calculation is not possible for real castings.

The formation of fine structures is connected with an increase in surface area and **surface energy** leading to back-pressure p_s. For

simplified models and estimated values for the surface tension approximations can be made.

Melts of jewelry alloys cast in protective atmosphere do not wet investment walls. **Capillary force** tries to 'push back' the melt especially in fine structures, and an equivalent back pressure is created. The pressure depends on surface tension, wetting angle and diameter of structure element. In simplified cases the back-pressure can be approximately calculated for rods and wires. Casting on air causes wetting of the investment by the oxidized melt. The capillary back-pressure disappears, and a positive capillary force could even improve formfilling. However, other disadvantages are related with casting on air, which weigh out the positive effect of reduced capillary back-pressure.

Residual gas within the pattern escapes through the pores of the investment. The diffusion of gas is a function of time. Therefor at the moment of casting an increase of pressure is observed. The gas can not escape as fast as the melt flow compresses the gas. The increase of pressure could be measured experimentally. Fig. 3 shows an example. Vacuum assisted casting equipment was used. With full vacuum applied only a moderate and short back-pressure occurred. Casting without vacuum (that is: without additional pressure difference p_3) causes a considerable increase of pressure. The pressure exceeds the atmospheric pressure and is only slowly reduced to the initial value. The delay exceeds the solidification time of melt in fine structures.

Extended experiments showed that the back-pressure is not very reproducible even under well controlled standard experimental conditions. It depends also strongly on the kind and shape of the patterns. Of cause the gas permeability of the investment plays a deciding part.

For this reason in modeling the casting process only a roughly estimated moderate value for gas pressure will be used.
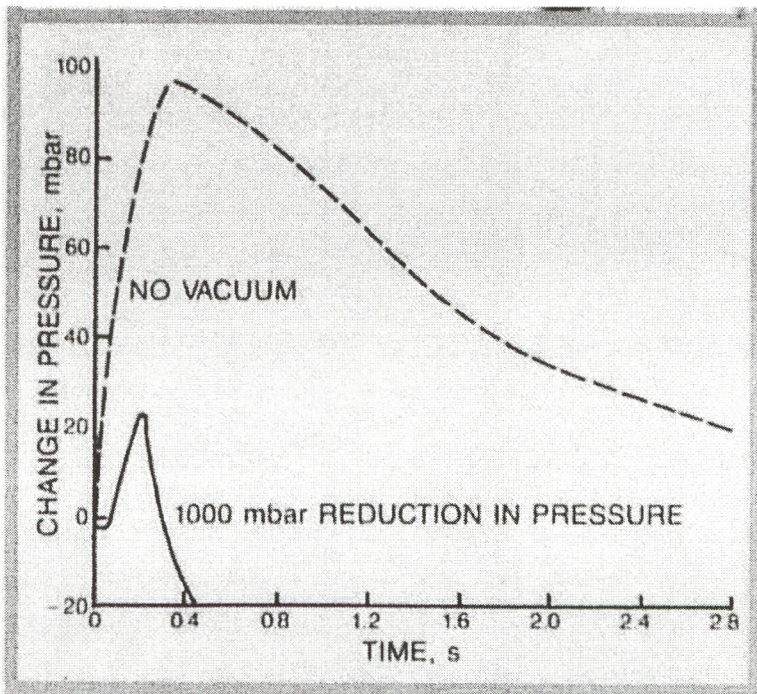
Fig. 3
Changes in gas pressure within the flask.
Vacuum assisted casting equipment, full vacuum and no vacuum applied

Last but not least a **balancing pressure p_s** was introduced in the balance of pressure. Changes in cross-section and bends in the structure cause additional back-pressure. They are obstacles in the flow and the pressure increases with the sharpness of edges or bends. Smooth structures should be preferred. Measuring this kind of back-pressure is not possible within the complicate structure of an investment casting. However, some estimate can be made using rules developed in hydro-mechanics. Fig. 4 shows the influence of edge shape if a rod is changing in diameter. A thicker rod is reduced to a smaller diameter. The edges (on the change-over) may be sharp or somewhat rounded ('broken') or the change-over is performed very smoothly (trumpet-like). The influence is strongly dependent on flow rate. At a low flow rate the effect might be neglected. However, with higher flow rates (e.g., within the sprue) there is a significant effect. In this place the flow rate is high.

An even more pronounced effect show bent structures. This can be demonstrated with a bent rod (fig. 5). The influence is illustrated for different flow rates and a14 ct alloy.

This fact should be kept in mind not only with designing the jewelry item itself but also when using a more complicated bent gate (sprue).

Evaluating a model

A tentatively sketched model shall demonstrate the effects of some factors. Of course rough approximations had to be made and the model was strongly simplified.

The basis of the model is casting rods of several diameters. Beginning with a wire of 0.4 mm (representing a filigree structure) up to a 2 mm rod (almost the size of sprues). The parameters used for modeling are summarized in table 3.
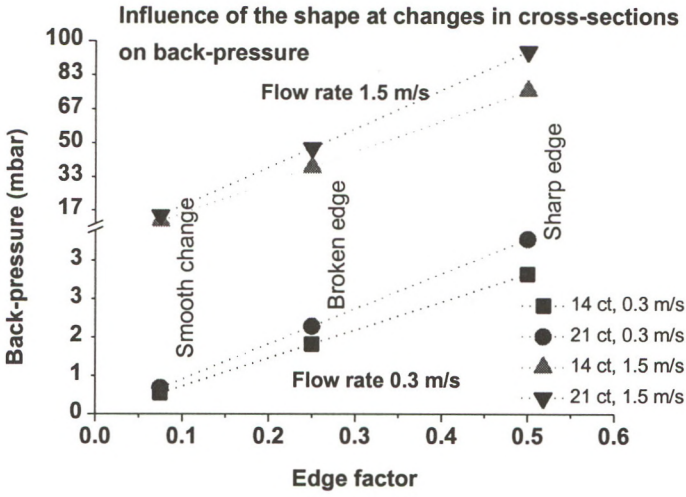
Fig. 4
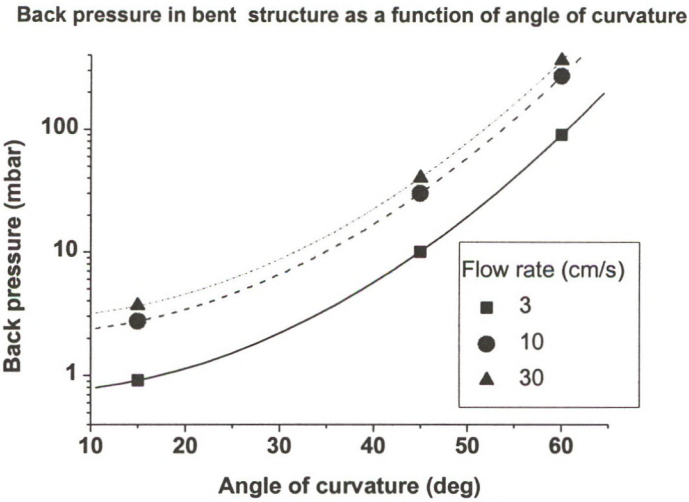Influence of the edge at a change in cross-section (diameter) of rods

Fig. 5
Back pressure in bent structure as a function of angle of curvature

Table 3 Parameters used for modeling

Alloys	14 ct, 21 ct (density 13.5, 16.9 g/cm³)
Casting method	Combined method
Estimated values for material constants	
Dynamic viscosity	$4.5 * 10^{-3}$ Pa/s
Surface tension σ	1.2 J/m²
Wetting angle	140 °
Dimensions:	
Distance crucible/flask	50 mm
Central sprue	10 mm diameter/ 150 mm length
'Cast items'	Rods 50 mm length/ 0.4, 1 and 2 mm diameter
'Standard' flow rate at filling the rods	0.3 m/s
Pre-defined pressures	
Additional (filling) pressure p_3	500 mbar
Gas (back-) pressure p_g	20 mbar
Balancing (back-) pressure p_s	50 mbar

Fig. 6 gives a first impression on residual pressures for two rod diameters and different filling pressures. For formfilling a positive residual pressure is necessary. An excess will be used for increased filling flow rate (see later). A rod with 0.4 mm diameter can only be filled with additional pressure. Without this no positive value for the residual pressure is achieved.

A rod with 1 mm can only be filled without additional pressure if it is positioned near the bottom of the tree. The distance between crucible and flask (height of drop) plays also a part.
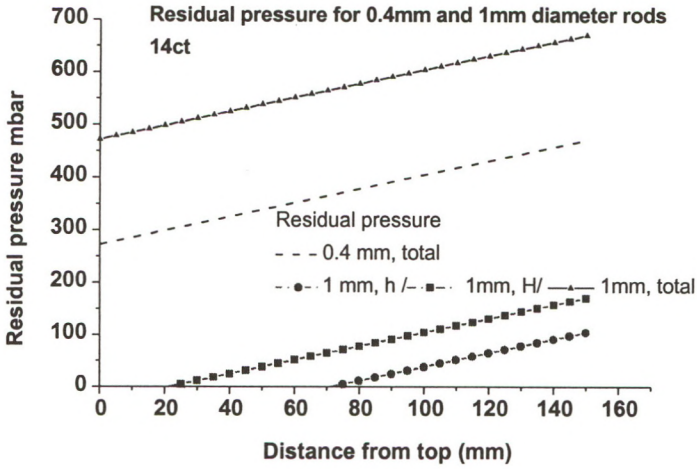
Fig. 6
Residual pressure as a function of column height and rod diameter
(computed with: p_1 static pressure due to column height h, p_2 pressure due
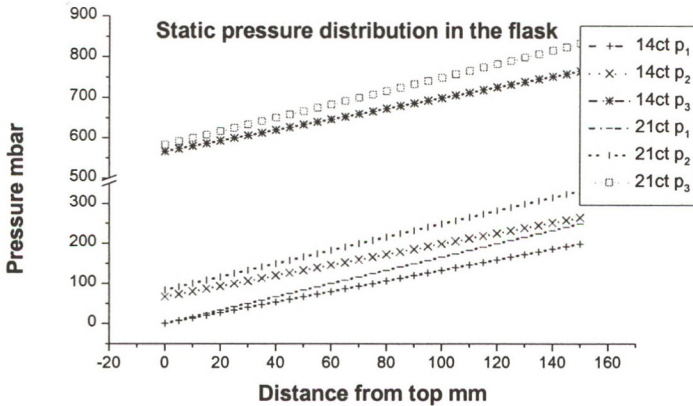to total height H -see fig. 1-, p_3 total pressure)

Fig. 7
Dependence of static pressure on column height h
(computed with: p_1 static pressure due to column height h, p_2 pressure
due to total height H -see fig. 1-, p_3 total pressure)

Fig. 7 shows for comparison the pressure distribution in the hypothetical case of static liquid equilibrium (never obtained with investment casting).

The magnitude of different kinds of back-pressure is demonstrated in fig. 8 (21 ct as an example). The flow pressure does not include edge and bend effects. The pressures caused by melt flow and by surface tension are strongly dependent on rod diameter (with the given preconditions). Back-pressure caused by capillary force is the smallest one. Fig. 9 and 10 show the relative contribution of the three types of pressures.

Some interesting information could be obtained by computing the flow rate for different rod diameter. The rods were thought to be fixed near the bottom of a tree.

A laminar flow model was used for computing (fig. 11). The smallest diameter can not be filled without additional pressure (flow rate approximately zero). The flow rate of the larger diameters would exceed the critical flow rate at these conditions. That means that the flow will be changed from laminar too turbulent. The computed, extremely high flow rate (hollow symbols in fig. 11) is not real. The rate will be significantly reduced by turbulence. The turbulence effect could not be included in the simulation yet because of missing data.

A conclusion for practical work is: Under conditions well suited for filling fine structures undesired turbulences occur in heavy cross-sectioned parts. That is one more reason for not mixing heavy and light weighted items.

Some results from experimental work shall illustrate the modeling procedure. Spirals made of wax wire were horizontally positioned in varying height on the central sprue. The relative formfilling (filled length /total wire length *100) was measured. Fig. 12 shows the results of casting in a closed chamber without additional pressure. Casting in vacuum avoids back-pressure by gas. Fairly good formfilling can be achieved at the bottom of the tree (pressure p_2 at its
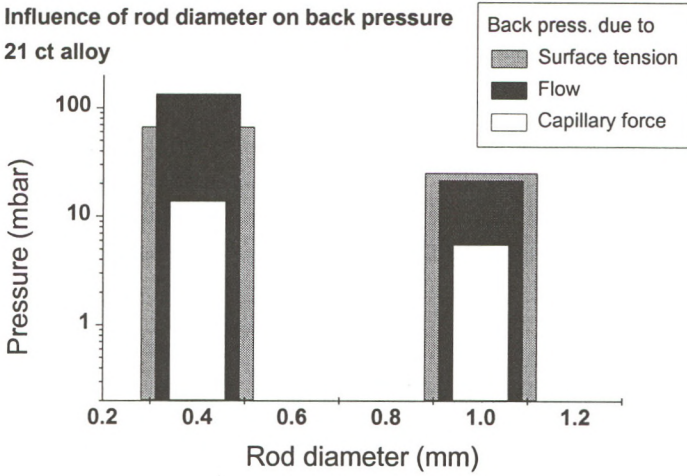
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Fig.8
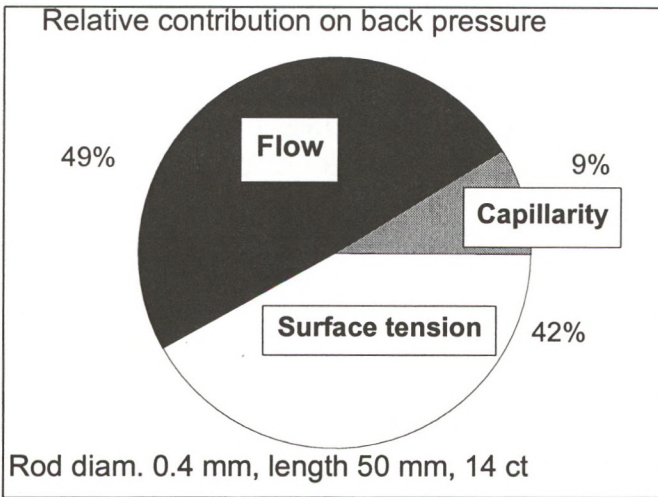Magnitude of different kinds of back-pressure

Fig. 9
Relative contribution of different kinds of back-pressure on the entire
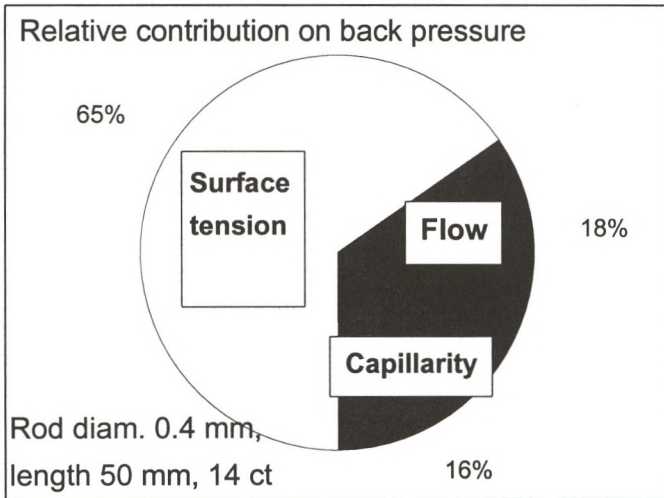back-pressure
Rod diameter 0.4 mm, 14 ct alloys

Fig. 10
Relative contribution of different kinds of back-pressure on the entire
back-pressure
Rod diameter 2mm, 14 ct alloys

maximum). Gas pressure reduces the formfilling considerably. Near the top formfilling is poor in any case.

Additional pressure makes the formfilling more uniform in the case of an initial vacuum (fig. 13). Even if a relative low initial gas pressure is present, the improvement in formfilling is moderate. Remarkable is the decrease of that value at the bottom of the tree. Normally an increase in formfilling is expected with increasing column height. This result could be interpreted as the influence of turbulence.
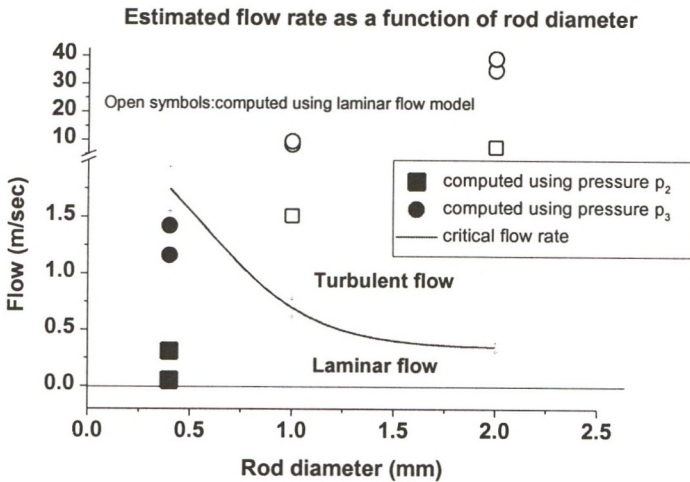
Estimated flow rate as a function of rod diameter

Fig. 11
Flow rate as function of rod diameter. Estimations were made using a laminar flow model.
(computed with: p_2 pressure due to total height H -see fig. 1-, p_3 total pressure

Fig 11
Flow rate as function of rod diameter. Estimations were made using a laminar flow model.
(computed with p_2 pressure due to total height H –see fig. 1-, p_3 total pressure

Formfilling of spirals as a function of distance from top
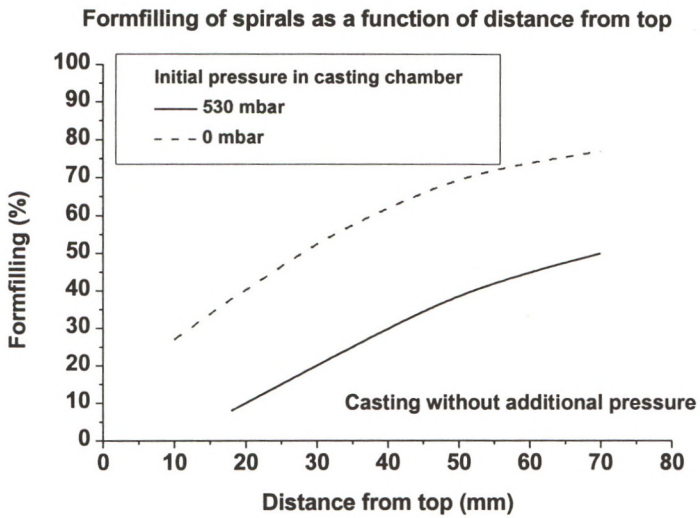

Fig. 12
Formfilling of spirals without additional pressure and with different initial
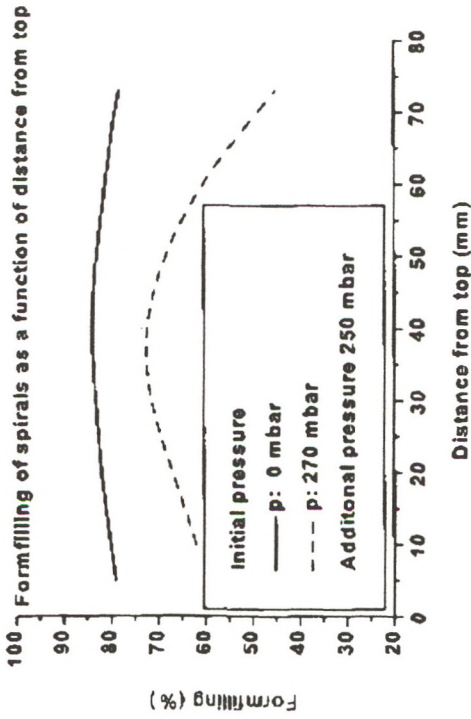pressure in the casting chamber (14 ct alloy, casting temperature 1050°C)

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Fig. 13
Formfilling of spirals with additional pressure and with different initial pressure in the casting chamber

Centrifugal casting

Modeling centrifugal casting is more difficult; more parameters have to be included in the model.

The best method is treating the procedure analogue to static methods with some modification.

Fig. 14 shows centrifugal casting equipment diagrammatically. Dimensions used for modeling are drawn in.

In a first attempt a model with constant speed of rotation was developed. In this model gravity is substituted by centrifugal acceleration. Gravity is – at a given geographic location – a constant which can not be influenced. Centrifugal acceleration, however, is influenced and determined by the dimensions of the equipment and the speed of rotation. For modeling only some typical examples can be considered. The values used for computations originate from real casting equipment.

Fig. 15 compares the hydrostatic pressure within the central sprue for both casting procedures. Whereas the hydrostatic pressure caused by gravity increases linearly with column height shows the column pressure in centrifugal equipment a parabolic function. That means that a pronounced effect of column height on formfilling could be expected with centrifugal casting. An equalizing effect of additional pressure (as it is the case in static casting) can not be obtained.

Fig. 16 compares the residual pressures for casting a rod of 1mm diameter. Static casting without additional pressure is in the same range as centrifugal casting with 400 rpm. With additional pressure the static casting is – following the model- superior to centrifugal casting with 400 rpm. A speed of rotation as high as 800 rpm is necessary to obtain complete formfilling. It has to be taken into account that standard centrifugal machines have frequently no possibilities for applying reduced atmospheric pressure. In this case a relatively high back-pressure will occur (fig. 17).
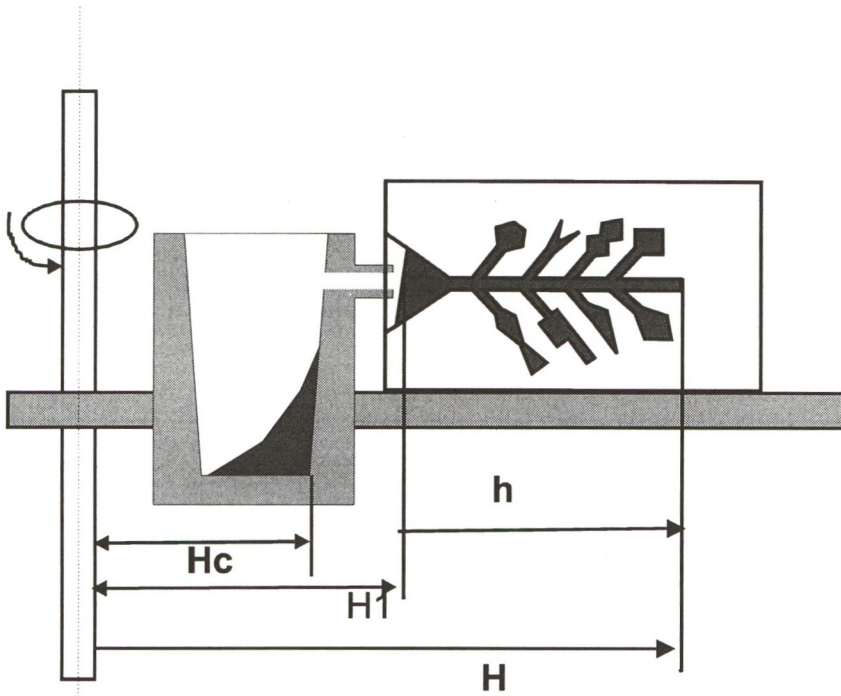
Fig. 14
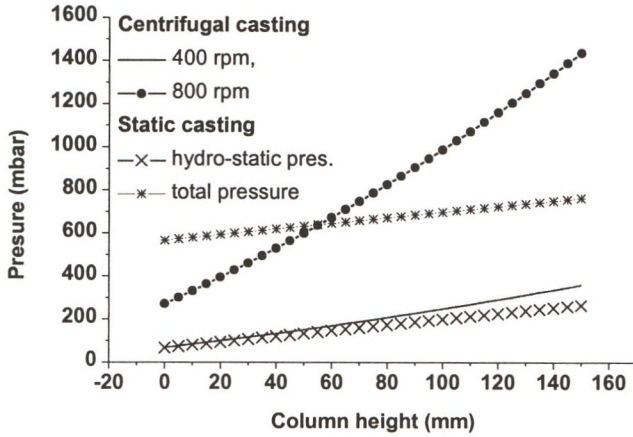Diagrammatic principle of a centrifugal process

Fig. 15
Comparison of pressure of static and centrifugal casting
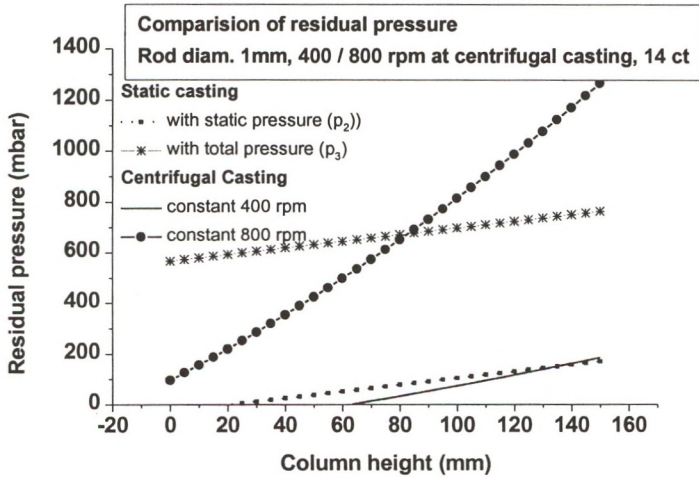(*computed for constant speed of rotation*)

Fig. 16
Residual pressure for casting a 1mm diameter rod (14 ct alloy)
Comparison of centrifugal casting with static casting
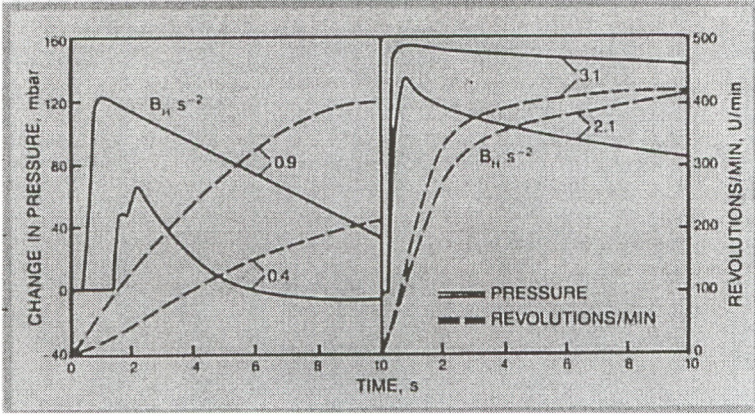(*computed for constant speed of rotation*)

Fig. 17
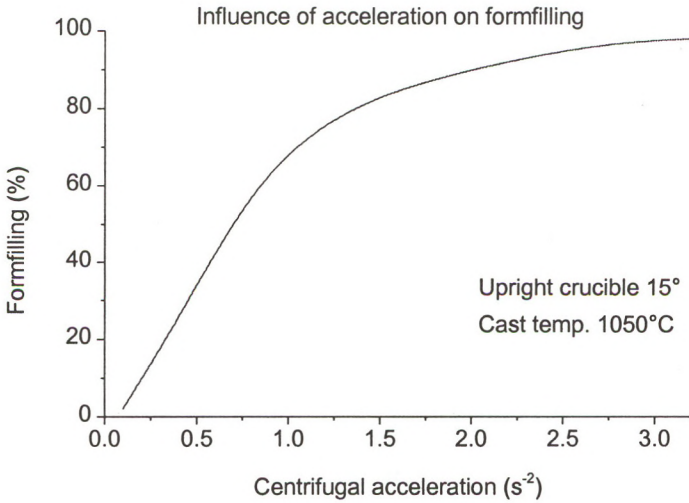Effect of acceleration and speed of rotation on back-pressure

Fig. 18
Formfilling as a function of acceleration using of an vertical crucible
with a wall inclination of 15 °

Of course changes in geometry and/or speed of revolution can increase the pressure. However, technical limits will not allow principal changes.

This high speed of rotation necessary for formfilling is very surprising and caused some doubts on the validity of the model. There is a strong contradiction to experimental data obtained formerly.

An important result of experiments was that the fine details were already filled before a constant maximum speed of rotation was reached. The acceleration has an important influence on formfilling. Low acceleration causes low formfilling, with increasing acceleration formfilling is increasing, too.

The positive effect of acceleration can be explained as follows.

A droplet of melt can not leave cylindrical crucible in an exactly upright position, independent of speed of rotation or centrifugal force. The crucible must be conical shaped or tilted to some degree. The critical angle (measured against the vertical) depends on the distance of the crucible from the center of motion and on the speed of rotation. Based on the model mentioned above an optimum inclination of the crucible walls could be expected at approximately 10 to 15 °. Increased inclination would enable the droplet leaving the crucible at low speed of rotation and causes premature filling the flask. The melt should fill the flask at an appropriate high speed of rotation to ensure filling of fine details in a short time.

In reality the crucible is not filled with a drop of melt but contains some centiliters of liquid. Influenced by centrifugal force the liquid builds up its own 'wall' and will start flowing at a lower speed of rotation. The filling time of the flask will occur in a certain range of speed of rotation. For filling the flask entirely in a short time a high acceleration is necessary covering the critical speed range in a time as short as possible.

Fig. 18 and 19 show two examples for the influence of acceleration on the formfilling of standard grids. The vertical crucible with a wall inclination of 15 ° produces good formfilling. The reproducibility of the results is satisfactory. The tub shaped flat crucible produces worse formfilling. The values scatter widely.

This 'crucible effect' can not explain the rule of acceleration fully. More investigations are necessary

Thermal problems

Thermal processes build the second principal group of physical processes in investment casting.

The solidification of the melt influences a variety of properties: formfilling (as already mentioned), micro-porosity (shrinkage porosity) grain size, segregations and dendritic structure, surface quality. Heat transfer also is also of great importance when chemical reactions between alloy and investment occur.

Main influencing factors are (some more factors may be found):
a) Specific heat and heat of solidification (equivalent to heat of fusion) of alloy
b) Solidification range of alloy
c) Shrinkage of alloy at solidification
d) Thermal conductivity of investment
e) Specific heat of investment
f) Mould (flask) temperature
g) Melt (casting) temperature
h) Size and shape of the item to be cast

Establishing a model of thermal processes would exceed the scope of this presentation. It should be reserved for an other project.

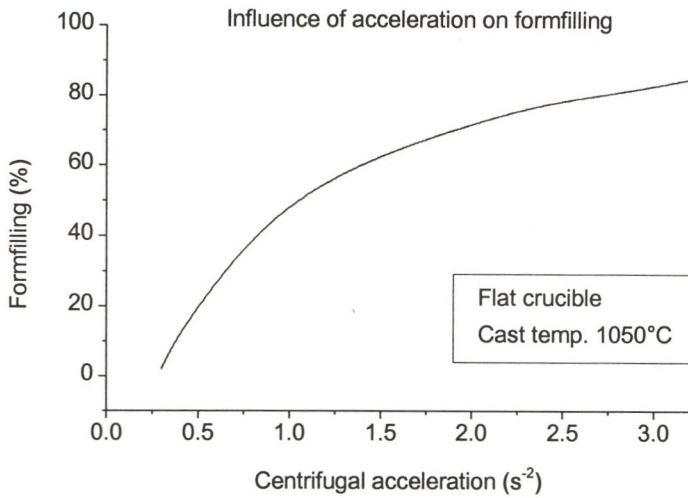However, results of experiments shall demonstrate points of interest.

Fig. 19
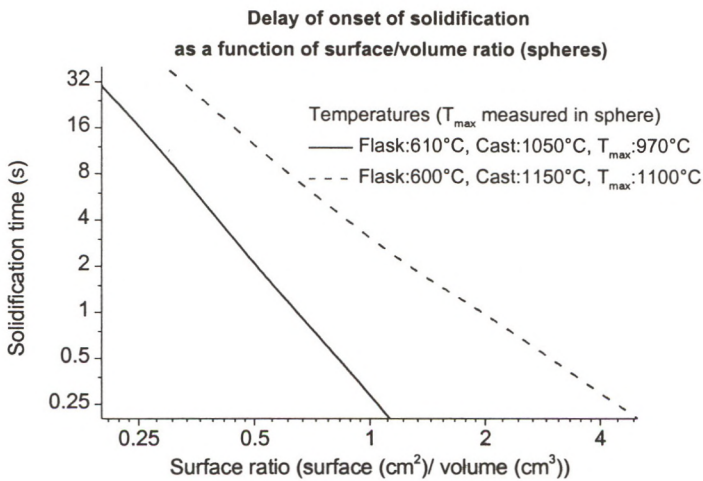Formfilling as a function of acceleration using an flat crucible.

Fig. 20
Relation between onset of solidification and surface/volume ratio
18 ct alloy). Casting temperature as parameter

Solidification time

Two different situations have to be considered:
a) Formfilling is definitively determined by onset of solidification
b) Shrinkage porosity, segregation and grain size are influenced by the time between onset and end of solidification (solidification interval)

Factors influencing these parameters have been already mentioned.

One of factors is the surface to volume ratio. It could be demonstrated that the onset of solidification is a linear function of the surface/volume ratio (both variables as logarithms, fig. 20)

For example, for rods of 1 mm diameter and 50 mm length the time elapsing before onset of solidification might be less than 0.5 sec (depending on casting temperature). It should also be noted that an increase in melt temperature of about 200 K ('°C') can prolong the solidification onset up to one magnitude.

The solidification interval is much longer. It reaches from approximately 10 sec with smaller items up to more than 100 sec for a sphere with 10 mm diameter (fig. 21).

The cooling behavior is strongly influenced by the thermal conductivity of the investment. The specific conductivity was measured as 0.50 W/(m*K). It is equivalent to the conductivity of insulating bricks.

Formfilling is favored by this property, if ever influenced. The effect on shrinkage porosity is not yet clearly evaluated. Results of experiments are contradictory.

Temperature gradient

One advantage of the insulating property of the investment is a steep thermal gradient. The heat is transported very slowly. The different cast items are insulated and normally prevented from thermal influences by other items.
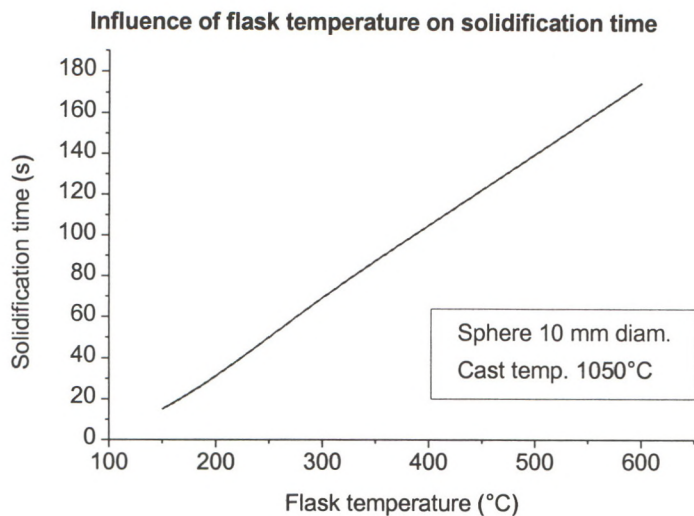
Influence of flask temperature on solidification time

Fig. 21
Solidification interval of a 10 mm sphere as function of flask temperature

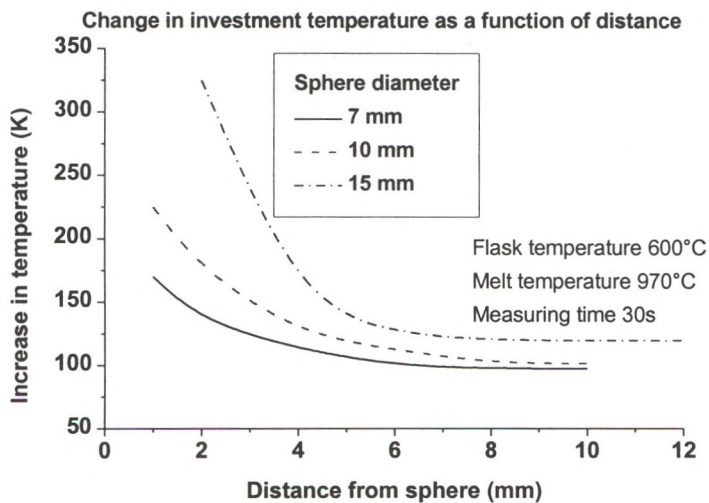**Change in investment temperature as a function of distance**

Fig. 22
Penetration of heat into the investment at casting of spheres
(Measuring time 30 s)

For example in a distance of 4 mm from the surface of a 10 mm sphere a temperature increase of approximately 120 K (°C) is measured 30 sec after filling the pattern (fig. 22).

Only very unfortunate conditions so-called 'hot spots' will influence the solidification.

Metallurgical factors

The formation of the microstructure at solidification causes numerous problems. In short some problems will be mentioned:

Grain size

The grain size is primarily a function of nucleation. It is influenced by the cooling rate in the critical solidification range and by characteristics of alloys.

Unfortunately carat yellow gold tends to form large grains. Increasing the cooling rate is not possible without impact on formfilling and possibly shrinkage porosity. Grain refining additions such as ruthenium may be used. However their appliance is difficult and needs precautions.

Dendritic structure

Dendrites are formed at solidification of metals by directional growth of the crystallites. Due to segregation during the solidification considerable differences in concentration between the primarily formed dendritic 'branches' and the finally solidified melt in the space between the branches may occur.

Dendritic structure causes some detrimental effects:
Limited corrosion resistance due the concentration gradient within the structure.

Increasing the tendency of shrinkage porosity by formation of a dendritic network (like a 'sponge'). The network hinders the melt flow,

which is necessary to compensate the volume reduction caused by shrinkage (see later)

Formation of a rough, 'dendritic' surface on heavy cross-sectioned items. There are two possible causes:
a) The residual melt between the branches is forced back by capillary force. This happens when the melt does not wet the investment. This is the case with casting of yellow gold in protective atmosphere. Casting pressure and temperature have also some influence.
b) Reaction of melt with the investment causes formation of sulfur dioxide. The gas generation may also 'pushes back' the residual melt from the surface. The heavy dendritic structure on the central sprue occurring at casting in reductive atmosphere or at high temperature is a perfect example.

Shrinkage porosity

The estimated shrinkage of jewelry alloys at solidification is approximately 10 %. In theory the shrinkage can be balanced by additional melt supplied from the (still liquid) central sprue through the gate. Premature freezing of thin walled parts and formation of a dendritic network hinder this process. Pores are formed between the branches of the primary dendrites.

Chemical reactions

Two kinds of chemical reactions have to be mentioned in the first place: reaction with the atmosphere (oxidation) and reaction with the investment.

Oxidation

Melting and/or casting on air causes oxidation of alloying compounds in different ways:

    Gold itself, of course, is inert.

    Silver does not form stable oxide, but dissolves a great quantity of oxygen (approximately 0.3 % in the melt at melting point). Even

solid silver can dissolve remarkable amounts of oxygen. Usually fine silver contains also oxygen. It is recommended to remove oxygen by melting of fine silver under reductive conditions before using it for alloying.

One common defect in silver (alloy) casting is 'dark spots'. The defect is not really a casting defect. It is caused by so-called inner oxidation, occurring at cooling down the flask. Oxygen diffuses into the surface of silver. Alloyed copper is oxidized, and forms a layer of copper oxide just beneath the surface.

Copper is easily oxidized to copper (II) oxide (in silver-copper alloys to copper (I) oxide), However, it can also readily be reduced by melting in reductive atmosphere or by covering the melt with charcoal. In gold-silver-copper alloys no special de-oxidizer is necessary to remove copper oxide. Adequate melting conditions are sufficient. After casting copper forms a voluminous dark layer on the metal surface which does not protect the metal. A different behavior shows *zinc*. Zinc oxide is more stable. Once formed it can no more reduced in a normal investment casting process. Formation of zinc oxide has to be prevented by using a protective atmosphere.

After casting zinc containing alloys forms a tense color-less layer on the surface, and prevent the material from heavier oxidation.

Silicon has similar properties like zinc. The stability of the oxide is even more stable. It prevents also the surface of a cast item from severe oxidation at cooling down. As well zinc as silicon produce a more shiny yellow surface of yellow gold castings.

Silicon is also used as a 'deoxidizer', an unnecessary measure in jewelry yellow gold alloys.

Chemical behavior of investment

The decomposition and reaction of investment with melt as the origin of gas porosity was already discussed in former publications.

Only a short note shall recall the facts. Preferably in reducing atmosphere and / or in the presence of reactive elements (e.g., nickel, higher concentration of zinc) the melt reacts with the investment under

formation of sulfur dioxide, silver sulfide, copper sulfide, and also oxides. Sulfur dioxide directly formed or formed at remelting sulfide containing material causes gas porosity. Exceptionally critical is remelting of material polluted with remainders of investment.