Investment Casting of Gold Jewellery

GAS PRESSURES IN MOULDS DURING CASTING: THEIR MEASUREMENT AND THEIR EFFECTS

Dieter Ott and Christoph J. Raub
Forschungsinstitut für Edelmetalle und Metallchemie, Schwäbisch Gmünd, Federal Republic of Germany.

The lost wax or investment casting process used extensively in gold jewellery fabrication is subject to the effects of a large number of process variables. One consequence of this is that where problems arise or exist in its application, they can be difficult to understand and solve. In order to promote optimization of the process the authors have studied the effects of a number of process variables. In this, which is the second in a series of articles* describing their findings, the authors describe, first, the methods they have used and secondly, the results of observations made of the gas pressures in moulds during casting and the effects of variations in these pressures upon the quality of the casting produced.

Experimental Methods

Test Models

Test castings were made using wax models of various shapes.

The stepped wedge model (Figure 1) had polished surfaces with dimensions of 10 x 30 mm, and with steps which were successively 8, 4 and 2 mm in height. Castings of this design were used for studying the effects of crystallization velocity and heat capacity upon the surface structure of castings and upon their texture as revealed by polishing.

The lattice or retention model (Figure 2) was similar to one used by the firm BEGO in Bremen. It had mesh dimensions of 1.8 x 1.8 mm and was 21 x 33 mm in size. This model was used as a means of assessing the mould-filling capacities of alloys of different compositions under different casting conditions.

The spiral model (Figure 3) had a spiral diameter of 60 mm, a length of 320 mm and a diameter of 0.2 mm. It was joined at right angles to the trunk of the casting tree and the distance penetrated into it by the molten metal during casting was used as a measure of

Fig. 1 Stepped model for determining the effects of crystallization speed and heat capacity upon surface structure and texture.

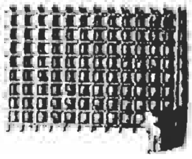


Fig. 2 Retention lattice model (Bego, Bremen) for determining mould filling power.

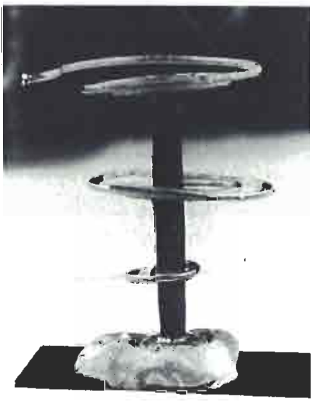


Fig. 3 Spiral model for determining mould filling or penetrating capacity.

Fig. 4 Dumbell model for density determination.

---

*A number of articles describing the effects of different process variables on the quality of carat gold jewellery made by casting will be published in forthcoming issues. These stem from a comprehensive research programme carried out at the Forschungsinstitut für Edelmetalle und Metallchemie, Schwäbisch Gmünd, Federal Republic of Germany. The series of articles will also be published in German in *Metall*. The first in this series, an historical review of the lost wax casting process, was published in *Metall*, 1981, **35**, (12), 1257 in English and will not be repeated in *Gold Bulletin*. Other articles which should be read in conjunction with this series are 'The Long History of Lost Wax Casting' by L.B. Hunt, *Gold Bull.*, 1980, **13**, (2), 63; 'Jewellery Investment Casting Machines' by P.E. Gainsbury, *Gold Bull.*, 1979, **12**, (1), 2; and 'Gold Casting Alloys. Effect of Zinc Additions on their Behaviour' by Ch. J. Raub and D. Ott, *Gold Bull.*, 1983, **16**, (2), 46.
Editor

the mould-filling or mould-penetrating capacity of the metal under the casting conditions used.

The gramophone record model used was 11 x 30 mm in size. From the detail in which the grooves or tracks of the record were reproduced it was possible to assess the capacity of the process, under the conditions used, to reproduce surface details and therefore to produce castings of high surface quality.

Specially shaped models were also made for studies of cavity and pore foundation in castings and for testing the tensile strength of castings. For the former, the models (Figure 4) were designed for density determinations and were 16 mm in length with the larger diameter 8 mm and the smaller diameter 2 mm. For the latter the models had a total length of 42 mm, the actual test section being 18 mm long and 3 mm in diameter. They were not made exactly as specified in DIN 13906 but were mounted on a base and cast with upward flow of metal (Figure 5). This procedure was found to have advantages over the DIN method.

The models were all designed so that, using about 220 g of metal, at least two could be attached to each tree. In this way the effects of a specific set of casting conditions on more than one property or attribute of a casting could be determined simultaneously.

They were prepared using cold-setting silicone rubber (Wacker, type RTV M 400). This has the advantages compared with vulcanised natural rubber of producing smoother model surfaces and of being less inclined to adhere to the wax models. The use of separation aids, with their adverse effects on model surface properties, could therefore be avoided. It has, however, lower elasticity, lower resistance to abrasion and a shorter life time.

The wax used was a commercial one of medium hardness with low shrinkage. It was selected on the basis of preliminary trials.

The trunk of the casting tree was cylindrical with a diameter of 7 mm. Greater diameters were tested in preliminary work, but gave no better results. Smaller diameters created problems in the attachment of the wax models, since the effects of differing hydrostatic pressures during casting became evident, according as to whether a test model was on the same or the opposite side of the trunk as that on which the molten metal was introduced.

Investing Procedure

The casting tree was embedded using either a calcium sulphate-bonded ('INVESTRITE', Hoben Davis) or a phosphate-bonded investment ('PLATINUM INVESTMENT', Shor). The former was used generally in the casting of carat gold alloys, and the latter was employed only in experiments which were aimed at determining the effects of sulphate in the investment medium upon the quality of castings.

Mixing of the investment medium was carried out mechanically in air, after which it was degassed under vacuum before being poured into the investment vessel. A further vacuum treatment was then applied, during which this vessel and its contents were subjected to vibration in order to remove air bubbles from the mass completely. When using calcium sulphate-bonded material, the invested mass was left to stand for two hours after it had set (20 minutes). With phosphate-bonded material, the setting process was longer (24 hours).

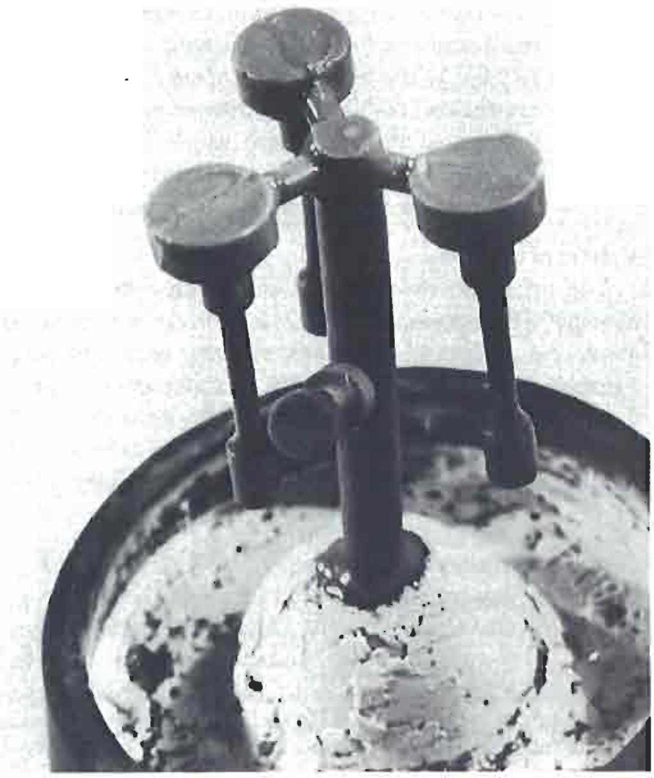


Fig. 5 Wax model used for making castings for tensile tests.

The melting out of the wax from calcium sulphate-bonded investment was carried out with steam which was found in preliminary tests to give better results than dry heat. The standard burning out process which followed embodied the following steps:

- Placing of the steam-dewaxed investment in an oven preheated to 150 °C, where it was held at this temperature for 4 hours
- Heating to 730 °C at a rate of 50°/h and holding at this temperature for 1 hour
- Cooling to operating temperature (usually 600 °C) where it was held for at least 2 hours to ensure uniformity in temperature.

In the burning out process special attention to the following points was necessary:

- Maintenance of very low heating rates over a relatively low temperature range (150 -250 °C) for a sufficiently long period to ensure complete removal of moisture within this temperature range. This avoided cracks forming when the mass was heated further

- Slow raising of the temperature above 250 °C, so as to ensure uniform heating of the mass
- Keeping of the maximum temperature reached by the mass below 780 °C, in order to avoid the sharp loss in the strength of the investment which occurs above this temperature. Such loss in strength can lead to poor casting surfaces and is especially significant in centrifugal casting.

Melting of the Alloys

The metal was melted inductively in crucibles which were normally of pure graphite, though in some instances ceramic coated graphite crucibles and quartz crucibles were used. The NiCr-Ni thermocouples used for temperature measurement were enclosed in a quartz tube, which dipped directly into the melt.

The standard alloy used in the tests was an 18 carat yellow gold alloy containing, by weight, 16 per cent silver and 9 per cent of copper.

Casting Techniques and Equipment

Jewellery investment casting machines have been reviewed by Gainsbury (*Gold Bulletin*, 1979, **12**, (1), 2-8). As pointed out by him,

> 'jewellery-type investment moulds cannot be filled by simple gravity pouring. The combination of unvented moulds with low permeability refractory, the need to reproduce fine detail and delicate sections, together with the relatively small size of melts and consequent low hydrostatic head and low thermal content of the metal preclude this possibility. Casting of the metal into the mould is therefore almost invariably carried out in some form of casting machine. A basic function of the machine is to apply pressure to the molten metal so that it penetrates and fills the mould completely. The same pressure may be used to effect transfer of the molten metal to the mould from the crucible when this is part of the machine. Centrifugal force, pressure or vacuum, or a combination of them are used to perform these two functions. The machine may also have built into it a means of melting the metal in a crucible or hearth in which the metal may be melted by external torch heating. Ancillary functions provided in the more sophisticated machines are melt temperature indication and regulation, atmosphere control and casting pressure regulation.'

In our studies, the following techniques were used: centrifugal casting, vacuum assisted static casting and static casting under vacuum or pressure in a closed vessel.

In centrifugal casting, a cylindrical crucible was used, of the normal type in use, with a metal discharge aperture in the front side. It was heated by an underlying flat element. The machine used ('PLASTICAST', Linn) was fitted with a simple tachogenerator for measurement of rotational speed, which was registered on a y-t recorder. From the recorded diagrams, it was possible to determine the angular acceleration at any desired points in time after the machine had been set in motion. The initial acceleration and the final rate of rotation reached were set manually by adjusting the torque. The maximum rate of rotation was 360 revolutions/min and the angular acceleration was varied from 0.4 to 3.5 s^{-2}. In addition, sliding contacts were fitted to the shaft through which temperature and pressure measurement signals could be transmitted from the rotating casting arm.

As regards the vacuum assisted static casting technique, it seems necessary to stress that the use of the term 'static' is misleading in that casting is always a dynamic process. In practice the use of the term implies that during the casting process the vessel containing the investment is kept static. Nevertheless in production practice using different types of casting equipment, there is scope for wide variations in the nature and magnitude of the forces acting on the melt during the casting operation. The types of vacuum-assisted static casting equipment used in our experiments are illustrated in Figure 6. In these, the investment container with a perforated cylinder wall and flange is fixed, using suitable sealing materials (asbestos, rubberised asbestos or asbestos-free substitute materials) in the cover of a vacuum chamber.

Before the metal is released or poured (see Figure 6) from the crucible the pressure in the chamber is reduced. This means that when the metal is released into the investment, the air which has to be displaced by metal from the cavities in the investment is sucked away through the porous investment. As a result, the pressure exerted by the molten metal in the mould is the sum of its hydrostatic pressure and the difference between the atmosphere pressure and the reduced pressure in the mould cavities. By altering the magnitude of the (reduced) pressure in the chamber, the pressure operating on the metal while filling the mould can therefore be varied.

Suitable ancillary equipment for the purposes of this investigation was assembled, using an available medium frequency generator (Leybold-Heraeus) and casting apparatus and accessories (Barrett). The crucible and its stopper were of pure graphite. In order to avoid oxidation of the melt, the crucible was blanketed with 'form-gas' (92 per cent N_2 plus 8 per cent H_2). In order to achieve good filling of the moulds when casting under controlled atmospheres in the sealed vessel it was found necessary, after pouring of the melt into the mould, to arrange an increased pressure differential by increasing the pressure in the melting and casting chamber immediately. A pressure reservoir was therefore connected via a tube of relatively large diameter with the casting chamber. By quick opening of a ball valve, the protective gas mixture entered the casting chamber rapidly, to increase its pressure there.

After giving them a rough preliminary cleaning by hand, the castings were washed in flowing water in an ultrasonic bath, and then brightened in a dilute pickling bath. Sand-blasting, such as is frequently applied in practice, was not used in this instance for cleaning because its effects on the surfaces of the castings were such as to obscure the causes of surface imperfections which arose during casting.

Pressure Relationships — Effect upon Casting Quality

Pressure relationships during casting have an important influence on the filling of the moulds and on the surface qualities

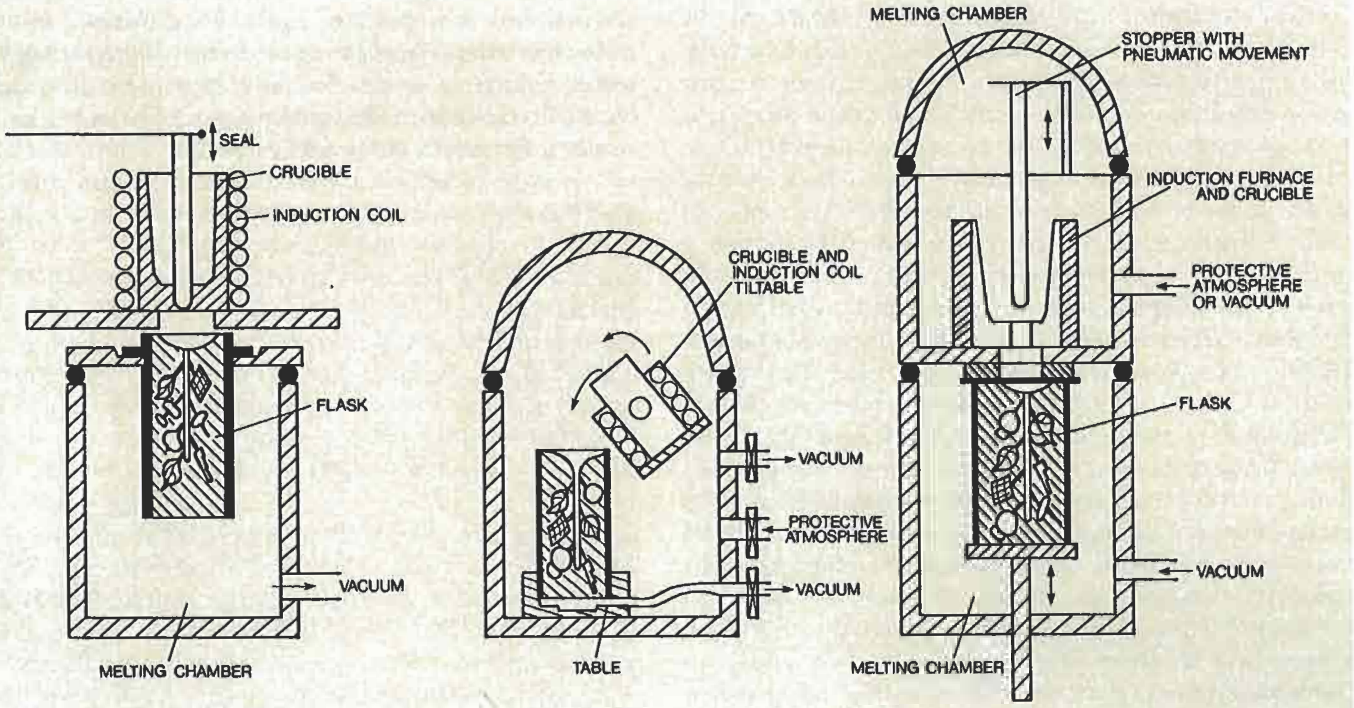


Fig. 6 Schematic diagram of static casting techniques.

of castings, especially their roughness and the accuracy with which they reproduce details of the surfaces of the models. If the pressure of the molten metal is too high, rough, sandy surfaces result (Figure 7). The metal penetrates the investment and, especially in the case of pieces of large diameter, a rough surface layer is formed which consists of a mixture of investment and metal, and which cannot be removed by ordinary pickling methods. If the pressure is too low, then the mould does not fill properly.

The flow of molten metal into the mould is resisted by the viscosity of the melt, surface and interfacial tension and the pressure of the gases which are trapped in the mould and have to escape through the investment. The gas pressure is not the same as the maximum pressure of the liquid metal, because the mould is porous and permeable and not hermetically sealed. The porosity of the investment and the pressure difference created in vacuum-assisted casting cause the gas pressures developed initially in the mould to fall fairly quickly. The critical factor for effective mould filling is the resultant effect — up to the point at which the melt starts to solidify — of the pressure of the melt and the counter-pressure of the trapped gases. Investigations of casting in vacuum have confirmed that the counter-pressures of the trapped gases are an important factor in ordinary casting, having a deleterious effect on mould filling. Their measurement under different conditions and in different types of equipment is therefore of special importance.

Measurements have been carried out using centrifugal casting equipment modified for the purpose, vacuum-assisted static casting, and static casting under both vacuum and pressure.

Fig. 7 Rough surface of an 18 carat gold casting formed under too high a pressure.

Measurement System

The measurement system was designed to make possible the determination of the pressure changes in the mould in relationship to the external pressure. It consisted of a probe, a pressure recorder and an indicating instrument. A tube of heat resistant steel (type 18/8), of external diameter 3 mm and internal diameter 2 mm, served as probe. To ensure a rapid response and to avoid error, the volume of the probe was kept to the minimum. The probe was attached to a branch on the casting tree carrying a tensile testing model with which it was invested. Its projecting end was cooled with water before casting, andconnected to the pressure recorder with a flexible tube. A solid-state recorder (National Semiconductor, type LX 1810 AN, pressure range 0 to 4 bar) was used. A 4-channel-recorder (Linseis), with rapid response time, made it possible to determine the pressure changes during casting over short times (< 1s). Temperature changes during static casting or rotation speeds during centrifugal casting could be recorded simultaneously in parallel. In centrifugal casting, measurements had to be transmitted from the revolving system. To avoid possible centrifugal effects the recorder was attached close to the axis of rotation. The connection with the end of the probe projecting from the mould was made with a short piece of tubing. Electrical connections, to carry input potentials and input signals, were made via a 3-pole sliding contact. The measurement signal from the tachogenerator was also recorded and indicated. A stroboscope was used for calibration.

In order to measure the pressure changes during casting with certainty, the probe was attached to the upper part of an upwardly cast tensile test model, as illustrated in Figure 8. The probe is located on a lateral extension of a tensile test model.

Fig. 8 Attachment of the pressure probe.

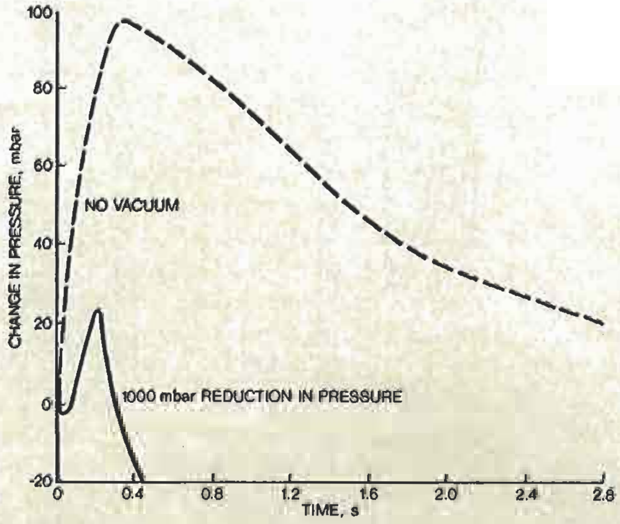
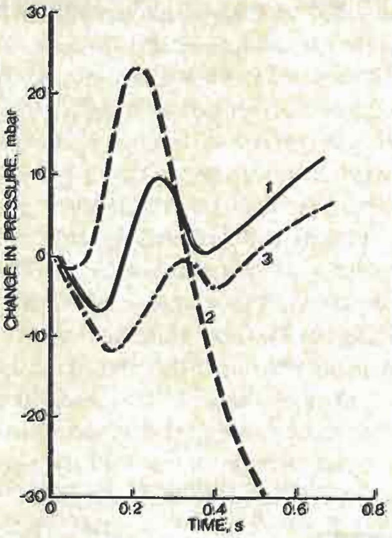


Fig. 9 Changes in gas pressure in a mould during static casting without and with a vacuum of 1 000 mbar in the casting vessel.

Fig. 10 Changes in gas pressure in a series of experiments under the same conditions and using a vacuum of 1 000 mbar.



Results

Vacuum-Assisted Static Casting

Typical examples of the pressure changes observed can be seen in Figures 9 and 10. If casting was done without reduction of the pressure in the casting vessel, the pressure rise inside the mould reached a maximum value of 98 mbar within 0.3 s, but fell gradually thereafter because of the permeability of the investment. The calculated static pressure at the foot of the casting tree was 120 mbar, at the level of the measuring point 54 mbar (static).

A rough estimate of the pressure increase arising from the kinetic energy of the melt, based on consideration of the dynamics of the casting process, was additional 100 to 120 mbar at the base of the tree and 50 mbar at the point at which measurements were made. The experiments showed therefore that the theoretically possible maximum pressure builds up momentarily when casting begins. It is not maintained, however, and falls away as trapped gases escape through the investment.

The situation is fundamentally different when the pressure in the casting chamber is reduced. Under these circumstances, the pressure drops as soon as casting begins and molten metal blocks the entry channel or sprue to the mould. The pressure wave caused by the melt reaches the measurement point after about 0.1 to 0.25 s, and the maximum pressure rise which develops after 0.2 to 0.4 s seldom exceeds 20 mbar. During the subsequent fall in pressure, the mould fills with metal and the tubular measurement probe usually becomes blocked also. In a few instances in which the latter did not occur, a rapid reduction in the pressure in the remaining unfilled space was observed. The maximum and minimum pressures reached during this typical sequence of events varied from one test to another, even when the conditions were unaltered. Moreover, in isolated instances, variations from this sequence occurred. Significantly, however:

- the maximum pressure seldom exceeded 20 mbar
- the pressures fell rapidly from their maxima to sub-atmospheric levels
- cavities of smaller volume filled progressively as the pressure fell and progressed to these levels
- the filling up of the mould was greatly accelerated by the sub-atmospheric pressures in the casting chamber.

Figure 11 illustrates the results of a test in which temperatures at the input port and inside the mould were measured as well as the gas pressures. The fact that the port temperature and the pressure changes occurred simultaneously demonstrates the instantaneous effect of the inflow of metal on the gas pressure in the mould. Nevertheless, the delay before the mould temperature began to rise shows that the filling of the mould occurs during the period of falling gas pressures.

An important factor determining the variations in the gas pressure in the mould is its permeability to gas, which is influenced by, *inter alia*, the proportions in which the investment material and water are mixed when it is prepared. Figure 12 illustrates the results

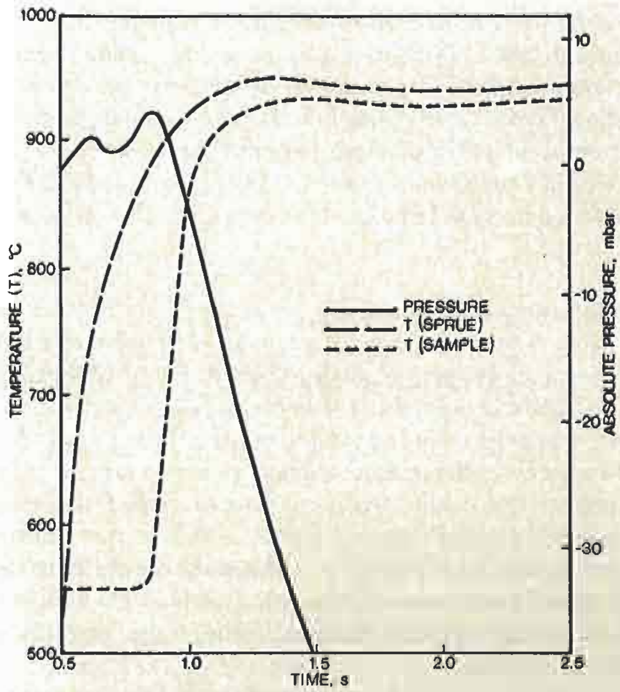
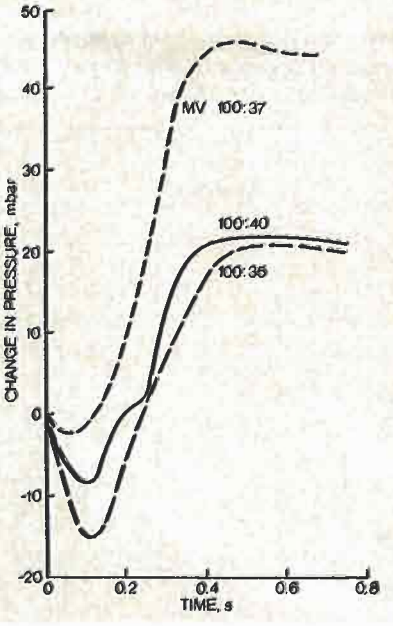


Fig. 11 Temperature and pressure changes in static casting.

Fig. 12 Effects of using different proportions of water and investment material in preparing moulds upon the pressure changes occurring in the moulds during casting (static casting and vacuum-assisted casting, reduction in pressure 1 000 mbar).



of experiments in which the mould was prepared using different ratios of water to investment material. The smaller amount of admixed water (37:100) gave a less permeable mould in which, correspondingly, a more rapid rise in gas pressure occurred on casting. The higher amount of admixed water (40:100) gave a more permeable mould, and a lower maximum gas pressure on casting. A very low proportion of water (35:100) gave a mould which developed cracks and which showed a very small rise in gas pressure on casting.

Static Casting Under Vacuum or Pressure

The gas pressure maxima in moulds observed under those casting conditions were found dependent on external gas presures. Table I shows the dependance of the maximum pressure differences observed in the moulds upon the initial gas pressures and the difference between the initial and final gas pressures in the casting chamber. The results from experiments carried out under apparently identical conditions show a wide scatter. Probable reasons for this are first that the conditions under which the melt was poured were not completely reproducible and secondly, that despite being prepared in the same manner, the gas permeability of the moulds varied.

However, in view of the poor reproducibility it seems possible, in retrospect, that the gas pressure peaks occurring in the moulds during casting are not influenced by the prevailing pressure conditions before and after casting. The average peak pressure in 21 experiments was 71 mbar. The pressure in the casting chamber before casting varied, however, from about 130 to 800 mbar, while the externally exerted pressure difference after casting varied from 0 to 667 mbar. The proven effects of the precasting pressure and the post-casting pressure differential are not in accord with the heights of the pressure peaks. A possible explanation is that by the time the pressure has reached a certain value (on average, 70 mbar), the melt has reached and blocked the pressure probe so that further pressure increases are not recorded. A limit to the gas pressure in the mould can also be imposed by the gas permeability of the latter. The speed with which the pressure rises and the metal flows into the small cavities of the mould is dictated by the external pressure relationships. The greater the speed, the more effectively can the molten metal fill the fine details in the mould surface before it crystallizes. An experimental demonstration of a dependence of the rate of the pressure rise on the external pressure relationships could not be obtained, because of the slowness of the measuring techniques. It must be borne in mind in this connection that the pressure changes occur within a range of 0.5 to 1.0 s.

Centrifugal Casting

The results obtained using the horizontally disposed crucibles, which were standard accessories of the machine, are illustrated in Figure 13. The effects of time, pressure and speed of rotation are shown in each curve. The torque and therefore the acceleration was varied between experiments. The acceleration of the machine is, as is to be expected, not constant under constant torque. In order to characterize the changes in angular rotation speed occurring with different torques, the half values $B_H(s^{-2})$ of the acceleration are plotted in addition to the maximum rotation speed U_{max} (min^{-1}). The values of B_H are those of the acceleration dU/dt at half the maximum speed of rotation, depending upon the acceleration.

As Figure 13 shows, the flow of metal into the mould begins at low acceleration after 1.3 s at an angular velocity of 30 min^{-1}. The casting arm has in this period moved through about one third of a revolution. The pressure reaches its maximum (65 mbar) after about 2.4 s at 60 min^{-1} and about 1.2 revolutions. The filling of the mould is by then completed though possibly not the finer details of it. Consequently, the gas pressure falls to nothing within 6 s. The reason for the small negative pressure of -5 mbar subsequently recorded is not clear. Nevertheless, this effect was definitely reproducible, provided that the melt did not penetrate the pressure probe and make observation of pressure changes which occurred at a later time impossible.

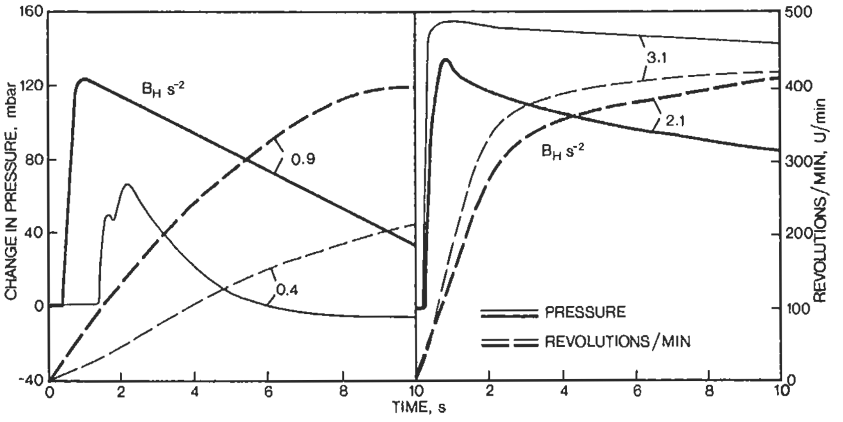
The maximum gas pressure which develops in the mould depends, as will be

Table I

Influence of Pressure Changes in the Casting Chamber upon the Gas Pressures in the Mould when Casting in a Sealed Chamber

Pressure in chamber, mbar			Max. excess pressure in the mould, mbar	Filling of Lattice, %	
Before casting	After casting	Difference		Above	Below
0	0	0	—	< 5	100
133	133	0	61	< 5	80
270	270	0	72,37	0	10
530	530	0	66,78,77	< 5	30
800	800	0	70	< 5	< 5
270	530	260	83,58,72	80	80
530	800	270	50	75	80
670	930	260	66,96,60,60,88,90,73		
530	930	400	73,77,60	75	80
133	800	667	63	99	95

Fig. 13 Dependence of the variations in mould gas pressure upon time in centrifugal casting using a reclining crucible, as a function of the acceleration (B_H). (Calcium sulphate-bonded investment A).



seen from Figure 13, upon the acceleration of the casting arm, this term being defined as the acceleration in the number of revolutions per minute and not as the centrifugal acceleration. The greater the acceleration, i.e. the steeper the slope of the curve showing the number of revolutions per minute, the higher is the gas pressure in the mould. The relationship between the half-value of the acceleration and the maximum gas pressure is shown in Figure 14 for two series of experiments using investments bonded respectively with calcium sulphate (A) and phosphate (B).

In the right-hand section of the figure the dependence of the maximum pressure upon the rate of rotation at this pressure is shown. The relationship is not as clear as it is when the half-value of the acceleration is plotted as the independent variable. Moreover there is a positive dependence between the rate of rotation at maximum pressure and the half-value of the acceleration. The speed of rotation at the point at which the gas pressure begins to rise when the metal enters the mould is relatively little affected by the acceleration of the system. The time taken for the pressure to reach its maximum, which is the time taken for the mould to become full varies from 0.5 to 2.5 s. The maximum rate of rotation has no effect upon the gas pressure changes, because the rise in pressure and the greater part of its subsequent fall have been completed before the maximum speed of rotation is reached.

The structure of the investment and, in particular, its permeability to gas, play an important role in centrifugal casting, just as they do in static casting. Figure 15 illustrates the changes in pressure and speed of rotation with a phosphate-bonded investment. In comparison with Figure 13, which illustrates these changes under approximately the same rotation rate, but using a gypsum-bonded investment (A), the maximum pressure reached is significantly lower. These differences can be seen also in Figure 14.

In some experiments a wax-filled quartz tube 5 mm in diameter

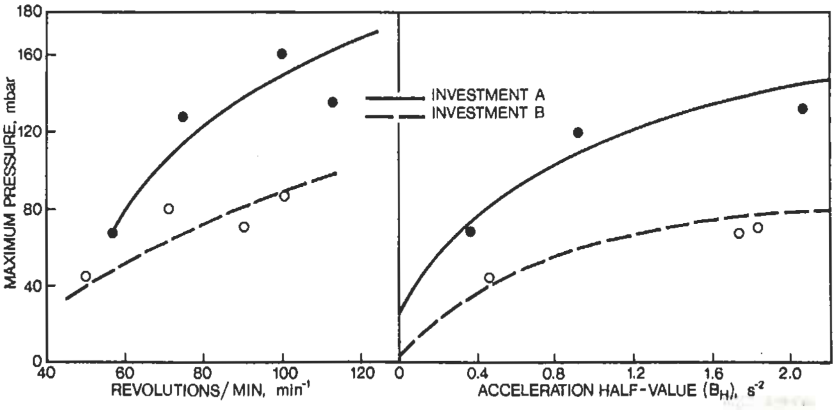


Fig. 14 Effect of acceleration of the rotation speed and the half-value of the acceleration (B_H) upon the maximum mould gas pressure reached when using calcium sulphate-bonded (A) and phosphate-bonded (B) investments.

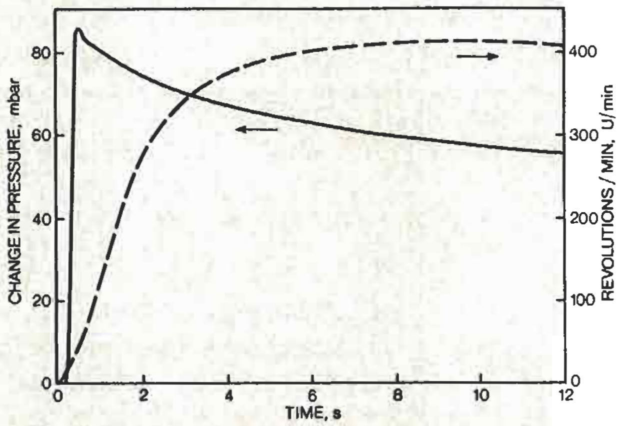


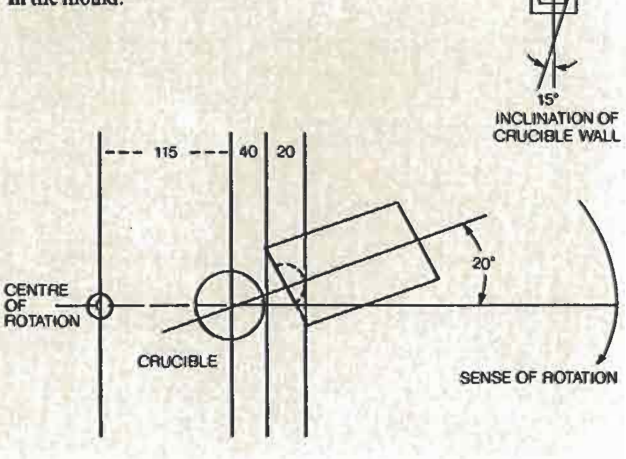
Fig. 15 As for Figure 13, but using a phosphate-bonded investment B and one acceleration $B_H = 4.6\,s^{-2}$.

was placed on the tree in place of the tensile test model. The open end of this tube carried the pressure probe and was sealed with an air-tight heat resistant material. The observed pressure, not affected by the permeability of the investment under these conditions, was about 180 mbar as compared with 120 mbar in 'open' measurements under the same conditions. This corresponds approximately to the maximum value of the pressure in the mould.

The Effects of Crucible Shape

A drop of metal cannot flow from a vertically standing cylindrical crucible when this is subjected to horizontal centrifuging. In practice, however, the wall of the crucible is never vertical, and the greater the angle at which it inclines away from the vertical the smaller is the limiting speed of rotation, and therefore the limiting centrifugal acceleration, at which the melt leaves the crucible. In practice, however, and apart from technical questions such as, for example, small irregularities in the shape of the crucible, two further factors must be taken into account.

Fig. 16 Geometric inter-relationships between equipment items in measurement of the effects of crucible wall slopes upon changes in pressure in the mould.



First there is in the crucible an appreciable volume of molten metal which, under the influence of the centrifugal acceleration, assumes a parabolic surface which permits flow of the metal from the crucible. In fact, depending on the maximum speed of rotation reached, a tongue of metal is left in the crucible. The formation of such a tongue is avoided, however, if the crucible walls incline outwards sufficiently. As a result of the sloping surface assumed by the molten metal, the angle of slope of which depends upon the rotation speed or centrifugal acceleration, the flow of metal from the crucible occurs over a certain range of rotational speed. The time taken for the metal to flow from the crucible is therefore also dependent upon the angular acceleration.

Secondly, under the operating conditions, the melt is subject to accelerated rotation, which gives rise to tangential acceleration. The force acting on the melt is the resultant of these two accelerations, centrifugal and tangential.

After it leaves the crucible, the melt is not subject to external forces and follows a course which relative to the mould has oppositely directed components in its rotational movement. The melt therefore strikes the mould at an angle to the radius against the direction of rotation. The casting results should thus be capable of being modified by adjusting the position of the mould.

To check this point, experiments were carried out in which both the crucible wall slope (standing crucible) and the orientation of the mould were varied. In Figure 16, the geometrical relationships in one experiment (crucible wall slope 15°, slope of mould 20°) are illustrated. Figure 17 shows the influence of the crucible wall slope on the pressure changes using a straight centrifugal arm (angle of arm, 0°). The speed of rotation at the start of casting (inflow of melt into the mould and gas pressure rise) decreases as the crucible wall slope changes from 5° to 8°. The measured values are unchanged at crucible wall slopes from 8° to 17°. This is not in accord with theoretical considerations, according to which a greater dependence on rotational speed and crucible wall slopes is to be expected. It is possible that a part of the melt rises parabolically up the wall of the crucible under the influence of the centrifugal forces, as already mentioned, and makes the effective crucible wall slope independent of its actual slope.

The maximum air pressure (P_{max}) in the mould rises with increasing crucible wall slope. This agrees with the above. With sufficiently large slope the melt flows from the crucible in a narrow range of rotational speed. The mould is filled rapidly and the rise in air pressure is correspondingly high. With steeper crucible walls the emptying of the crucible (rapid shooting up of the melt at crucible wall slopes dependent on the rotational speed) extends over a greater range of rotational speed and therefore over a greater period

Fig. 17 Influence of the wall slope of a standing crucible on the changes in pressure in the mould during casting, and the effects of time using a straight (arm angle 0°) centrifugal arm.

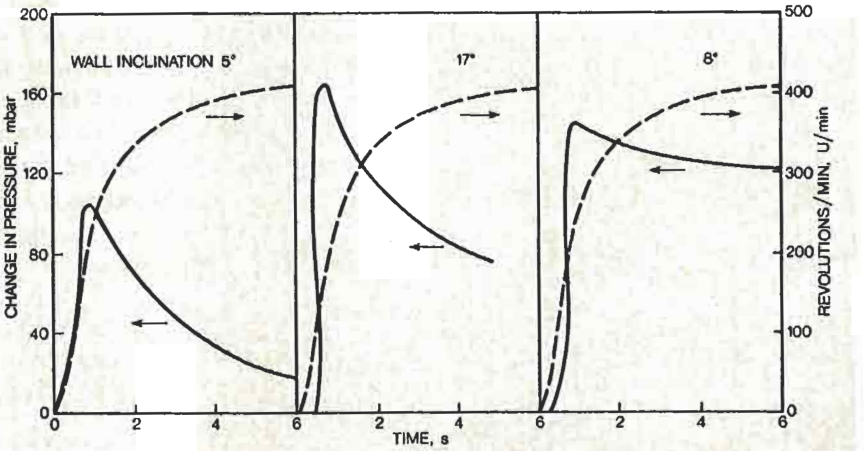
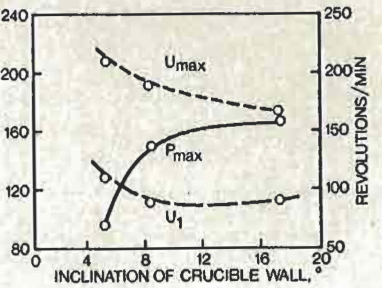


Fig. 18 Influence of the wall slope of the crucible on the maximum mould pressure (P_{max}), the speed of rotation on casting (U_1), and the speed of rotation at maximum pressure (U_{max}). (Acceleration B_H, 3.6 s^{-2}).



of time. The pressure rise is smaller, since there is time for gas to escape through the porous investment during the process.

In accord with the delay in the flow of the melt from steep-walled crucibles, and the consequent delay before the pressure in the mould rises, the maximum pressure using such crucibles is reached only at higher rotational speeds. Theoretically, these factors should have an effect upon the quality of casting. In a few experiments, though without measurement of the changes in pressure and rotational speeds, the effect of the angle of slope of the crucible wall on the filling of moulds was studied. A crucible wall slope of 15° to 17° was found favourable, but the results were not always reproducible.

Numerous experiments were then carried out with various arm-angles and crucible wall slopes. For each geometrical combination the dependence of the gas pressure developed in the mould upon the angular acceleration of the machine when the melt was discharged from it, was determined. The results of individual measurements showed a large scatter, and only by statistical evaluation of a number of results was it possible to recognise trends. These are illustrated in Figures 19 and 20. The most uniform data are those obtained with a reclining crucible and a straight arm. The air pressure in the mould over the lower range of values of the angular acceleration of the machine when the melt was discharged from it rose almost linearly with these values. Over the upper range of values, the maximum gas pressures reached in the moulds did not rise linearly and the curve flattened. The maximum pressures of 160 to 180 mbar which were reached are significantly higher than those reached in static casting. Using a straight arm and an upright crucible with walls inclined 15° to the vertical, the measured maximum gas pressures rose more slowly with increasing acceleration of the machine at discharge of the melt, and did not reach the high levels observed using a reclining crucible. They fell off rapidly at higher machine acceleration rates. This behaviour can be attributed to the fact that at higher accelerations on pouring there is considerable disturbance of the melt, which flows with greater turbulence under these conditions.

Experiments carried out with variations in the arm and crucible geometries (arm angles of 10°, 15° and 20°) gave results which were substantially similar, both qualitatively and quantitatively, in respect of the dependence of maximum gas pressures upon the machine acceleration at the point of discharge of the melt. It must therefore be accepted that in the range 8° to 17° the angle of inclination of the crucible wall has no demonstrable effect on the variations in gas pressure in the mould and therefore upon casting results.

With the mould inclined at angles of between 0° and 20° to the anticipated direction of flow of the melt on discharge, there was neither a positive nor a negative influence on gas pressures developed in the mould. Despite considerable variations in the geometry of the funnel feeding the mould, the melt was accepted

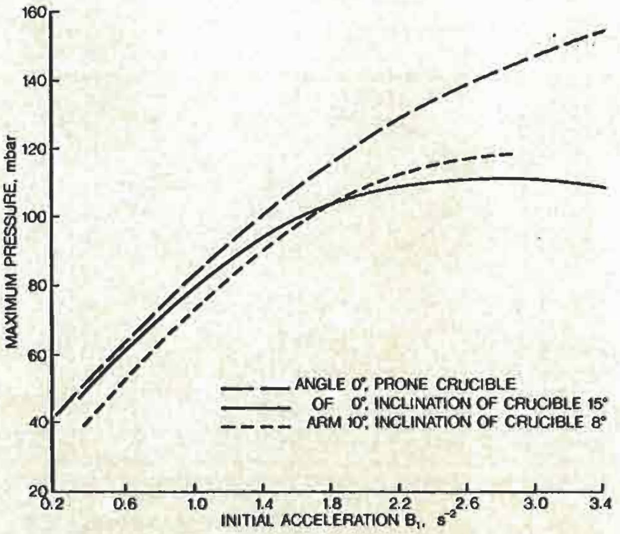
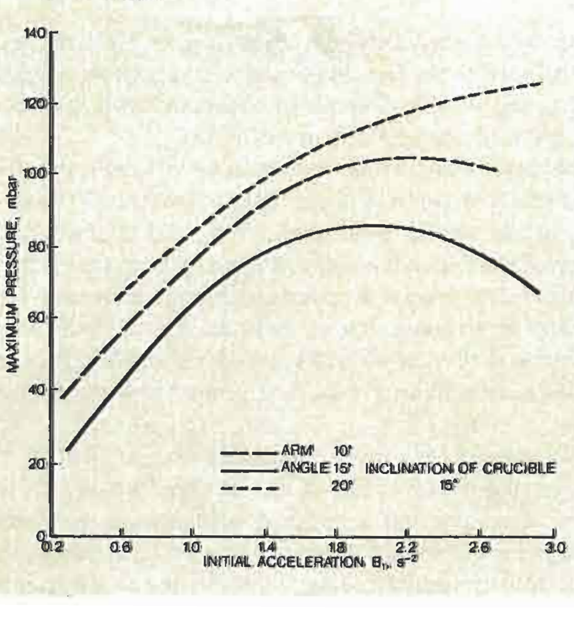


Fig. 19 Variation of maximum pressure in the mould (P_{max}) with the acceleration (B_1) on casting, using crucibles with different wall slopes and centrifuge arms with different arm angles.

Fig. 20 Variation of maximum pressure in the mould (P_{max}) with the acceleration (B_1) in casting, using the same crucible wall slope, but different centrifuge arm angles.



and guided into the central channel leading into the mould. The differences which certainly arise as a result of variations in the flow pattern of the melt have no sufficiently strong effect upon the pressures developed in the mould for there to be any discernible trends in the widely scattered results.

Summary and Conclusion

The measurement of the air pressure in moulds during the gold alloy casting process has been carried out using semiconductor pressure recorders. The investigations show that in the different casting procedures used this air pressure has a considerable influence on the course of the casting. In centrifugal casting it was necessary to record simultaneously the changes in the speeds of rotation of the machine. The findings deemed of most importance are:

1. The casting operation is completed in a very short period of time (about 0.4 to 0.5 s) in all processes. In the case of centrifugal casting an initial 'running-up' period of 0.5 to 2.5 s is required.
2. There are characteristic differences between the maximum air pressures as developed in the mould in the various casting processes.

In vacuum-assisted static casting, pressure peaks of at most 20 to 30 mbar develop, which rapidly subside under the influence of the reduced pressure in the casting chamber. As a result of the permeability of the investment this reduced pressure tends to extend to the unfilled portion of the mould during casting. When casting is carried out within a casting vessel, which is not evacuated, pressure peaks of about 70 mbar develop. The peak values observed in different experiments are widely spread but not significantly influenced by the external pressures before and after casting.

In centrifugal casting the rise in air pressure in the mould is influenced essentially by the angular acceleration of the machine at the point at which casting takes place. Depending upon this acceleration, peak air pressures of about 80 to 100 mbar are reached. The geometry of the casting arm and the crucible can be varied considerably without affecting the peak pressure significantly. The so-called reclining crucible appears preferable to 'standing' crucibles with walls having varying slopes (inclinations to the vertical). It gives more uniform and reproducible results. One of the reasons for this may be that the melt in the 'reclining' crucible has more scope for acceleration during discharge.

Acknowledgements

The authors are indebted to a number of organisations for support of this study. These include the International Gold Corporation, Limited, the Arbeitsgemeinschaft Industrieller Forschungsvereinigungen e.V., Köln, and member companies of the Deutschen Schmuckwaren-Industrie. They also wish to thank Drs. G. Gafner and W.S. Rapson for encouragement and assistance. The authors are further indebted to Dr. Rapson for the translation from German and substantial editing of this series of articles.